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REPORT OF A COMMITTEE

APPOINTED BY THE

LORDS COMMISSIONERS OF THE ADMIRALTY

TO CONSIDER AND REPORT UPON THE CONDITIONS OF

DEEP-WATER DIVING;

TOGETHER WITH

INDEX, APPENDICES, AND ILLUSTRATIONS.

AUGUST 1907.

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(C.N. 11713/19049.)

Admiralty, S.W.,
8th August 1905.

Sir,

With reference to Admiralty letter of the 19th July, C.N. 11713/17501, I am commanded by My Lords Commissioners of the Admiralty to inform you that they have decided to appoint a small Committee to consider and report upon the proposals which have been submitted to the Admiralty by Professor J. S. Haldane, viz. :—

(*a*) Improvements to enable men to dive in 30 fathoms of water and to do a normal amount of work.

(*b*) Certain experiments in connection with the effect of rarified air on the crew of a submarine boat.

The constitution of the Committee is as follows :—

Captain Frederick T. Hamilton, R.N., M.V.O., H.M.S. "Excellent," *President.*
Professor J. S. Haldane.
Captain Reginald H. S. Bacon, R.N., D.S.O. (Naval Assistant to First Sea Lord of the Admiralty).
Captain Edgar Lees, R.N. (Inspecting Captain of Submarine Boats).

I am to request that the President of the Committee will communicate with the several members as to the time and place for meetings of the Committee.

I am, Sir,
Your obedient servant,
C. I. THOMAS.

The Commander-in-Chief,
H.M. Ships and Vessels,
Portsmouth.

Note.—Staff-Surgeon Oswald Rees, M.D., was appointed to act as Secretary to the Committee on 20th October 1905.

Lieutenant G. C. C. Damant, R.N., and Mr. A. Y. Catto, Gunner, H.M.S. "Excellent," were appointed for the experimental work of the Committee.

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DEEP-WATER DIVING COMMITTEE.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS OF THE DIVING COMMITTEE.

SUMMARY OF MAIN CONCLUSIONS.

1. The respiratory distress, which under the present conditions of diving usually prevents divers from working at more than very moderate depths, such as 15 or 20 fathoms, is due to pressure of carbonic acid gas in the air of helmet, and can be entirely obviated by increasing the supply of air in direct proportion to its increase in absolute pressure. A table has been drawn up showing the air supply, rate of pumping, and number of men required for pumping, with the diver at different depths.

2. The test at present in use for proving the efficiency of diving pumps is quite unreliable, and many pumps in actual use, although they pass this test, are so leaky as to be very inefficient for work in deep water. Efficient pumps can, however, be supplied by the makers.

3. To obtain a sufficient air supply to enable a diver to work freely at depths from about 18 to 30 fathoms, it is necessary to couple together two efficient pumps of the ordinary Service pattern.

4. Practical trials have shown that with good pumps supplying the amount of air calculated to be necessary, a diver can work as comfortably at 30 fathoms, or more, as in shallow water, apart from the hampering effects of darkness and tide.

5. Experiments carried out in the steel chamber at the Lister Institute have shown that the serious dangers arising from the liberation of bubbles of nitrogen in the blood and tissues on the ascent of a diver from deep water can best be met by (1) limiting the time spent in deep water, and (2) ascending most of the distance rapidly, and afterwards making the last part of the ascent in stages, with stoppages interposed. In order to limit the time spent in deep water, the descent, and most of the ascent, should be rapid. This new method, which saves much time, besides being far safer, has been practically tested at sea up to 35 fathoms, the greatest depth hitherto definitely recorded as having been reached by divers, and a table has been drawn up showing time limits on the bottom, and the corresponding precautions recommended in ascending, for different depths up to 35 fathoms.

6. The risk of "blowing up" can be greatly diminished by lacing up the legs of the diving dress, and by abolishing the use of the "crinoline," which is a harmful encumbrance.

7. In cases of accidental "blowing up," or too rapid ascent, the danger from air bubbles in the blood can be avoided by sending the diver down again, even after serious symptoms have already developed, or by placing him in a re-compression chamber carried on the deck, and raising the air pressure.

RECOMMENDATIONS.

1. That it be made a routine practice to supply divers with the amounts of air which the Committee's investigations have shown to be required at different depths; and that a printed table showing the rate of pumping and the number of cylinders required at different depths be supplied with each diving pump.

2. That arrangements be made for regular and thorough testing of the diving pumps belonging to each ship, together with the air pipes, pressure gauges, and helmet valves, and for the making good of any serious defects; also that all new pumps and other diving apparatus be thoroughly tested on delivery.

3. That all new diving dresses be provided with an arrangement for lacing up the legs, as described in the Report, and that the issue and use of the "crinoline" be abandoned.

4. That a metal junction-piece for connecting together the air-supply from three pumps be supplied with each pump.

5. That a printed table (combined with that referred to in Recommendation 1) showing the precautions recommended by the Committee as regards limits of time in deep water at different depths, and stoppages during the ascent, be supplied with each diving pump.

6. That a new edition of the Diving Manual be prepared, containing, in addition to other information and instructions, a clear account of the physics and physiology of diving, and describing in detail the methods of carrying into practical effect the results of the Committee's investigations; also that corresponding practical instructions be given in connection with the diving courses for officers and men.

7. That, with a view of simplifying future investigation into this subject, any cases of illness caused by diving may be fully reported, with a statement of the depth of the dive, time on the bottom, and rate of descent and ascent, so far as known, and the report forwarded to the Admiralty for the Medical Director-General and embodied in the Annual Report on the Health of the Navy.

8. That investigation on the means of avoiding the difficulties and dangers met with in diving be continued.

F. T. HAMILTON, President,
Commodore, H.M.S. "Excellent."

R. H. BACON,
Captain, H.M.S. "Dreadnought."

J. S. HALDANE, M.D., F.R.S.

EDGAR LEES,
Captain.

OSWALD REES, M.D., Secretary,
Staff-Surgeon.

NOTE.—July 1906. The Report was written and transmitted to the Admiralty at the end of 1906. Its publication was, however, delayed pending the completion of a further extensive series of experiments at the Lister Institute. These experiments, which were carried out by Dr. A. E. Boycott and Lieutenant G. C. C. Damant, R.N., have thrown clear light on the precautions required for safely bringing divers, and other workers in compressed air, back to atmospheric pressure. The results, which are summarised in Appendix I., have enabled the Committee to prepare a Supplement (p. 57) specifying in detail the precautions required during the ascent of divers from different depths, and after different periods spent on the bottom. Towards the expenses of these experiments liberal contributions were made by three Engineering Firms—Messrs. John Aird and Sons, Messrs. S. Pearson and Son Limited, and Messrs. Price and Reeves—and by Mr. Basil P. Ellis.

A revised edition of the Diving Manual has meanwhile been prepared in accordance with the Committee's Sixth Recommendation.

We think that additional experiments on several points are much needed, but do not wish to delay further the issue of the present Report.

REPORT

TO THE

LORDS COMMISSIONERS OF THE ADMIRALTY

ON

DEEP-WATER DIVING

PRESENTED BY THE DEPARTMENTAL COMMITTEE APPOINTED TO INVESTIGATE
THIS AND OTHER SUBJECTS.

INTRODUCTION.

In accordance with our instructions to investigate the subject of Deep Diving in the Royal Navy, we have the honour to present to your Lordships the following Report :—

There are two special difficulties associated with deep diving under existing conditions. The first is that breathing is found to become very laboured at depths exceeding about 15 fathoms, the movements of the diver and his power of doing work becoming thus more and more limited, although men of exceptional skill and endurance have succeeded in working for short periods at as much as even 30 fathoms. The second is that shortly after the diver's return from deep water to the surface he may develop very serious symptoms, resulting sometimes in death, more frequently in paralysis, particularly of the legs and bladder (" diver's palsy ").

In connection with both of these main difficulties, and other subsidiary points, a large number of experiments have been carried out under the direction of the Committee. These were begun at Whale Island, Portsmouth, in an experimental diving tank, presented some years ago by Messrs. Siebe, Gorman, & Co., the first series being carried out by Dr. Haldane and Mr. A. Y. Catto, gunner, then chief instructor in diving at Whale Island. During the autumn and winter many further experimental dives were made at Spithead in depths up to 19 fathoms by Mr. Catto and several petty officers and men passing through courses of diving instruction; and numerous samples of the air breathed by the divers were obtained, and analysed by Staff-Surgeon Rees, who had meanwhile been appointed Secretary to the Committee, and who superintended the work. The leakage of the pumps, distribution of air in the helmet, and other questions, were also investigated at the Physiological Laboratory, Oxford, and Dr. Rees tested a number of diving pumps in use on vessels at Portsmouth. In April 1906 Lieutenant Damant was appointed for experimental work in connection with the Committee. Many further experiments were carried out at Spithead and in the experimental diving tank by him and Mr. Catto.

In view of the importance of investigating the means of avoiding the dangers of decompression, arrangements were made with the Director and Governing Body of the Lister Institute, London, by which, during June and July, Lieutenant Damant was enabled to co-operate with Dr. A. E. Boycott, of the Lister Institute, Fellow of Brasenose College, Oxford, in carrying out an extensive series of experiments on animals and men in a large steel chamber which had just been presented to the Institute by Dr. Ludwig Mond, F.R.S., and which proved of the utmost service. The expenses of these experiments were met by the Lister Institute. Lieutenant Damant and Mr. Catto also subjected themselves in this chamber to pressures which were gradually increased up to 30 fathoms of water, the maximum depth then contemplated by the Committee.

As sufficiently deep water was not available near Spithead, except where strong tides cause much delay in diving, arrangements were made to continue the work during August in or near Loch Striven, Argyllshire, from H.M.S. "Spanker," torpedo-gunboat, commanded by Lieutenant V. Dugmore. Precautions against dangers from decompression had been carefully thought out beforehand, but as a further safeguard means were also provided on board for prompt treatment of any symptoms. The diving was again undertaken by Lieutenant Damant and Mr. Catto, at depths which were gradually increased up to 35 fathoms, without oppression or ill-effects of any kind, and with full power of moving freely on the bottom and doing work. So far as we are aware this is the greatest depth ever definitely recorded as having been reached by divers, and considerably exceeds that at which work has hitherto been deemed to be ordinarily practicable.

As a consecutive account of all these experiments would be lengthy and confusing it will be more convenient to trace one by one the points investigated and conclusions arrived at. And since it was the respiratory distress in deep water, and consequent difficulty in working, which originally led to the inquiry, we may deal with this matter first.

Part I.

The Causes of and Remedies for Laboured Breathing in Diving.

To understand this subject it is essential to bear in mind the arrangement of the diving apparatus. The apparatus in common use in the Royal Navy is that supplied by Messrs. Siebe, Gorman, & Co., and is fully described in the Service "Manual for Divers," issued in 1904. The essential parts of the dress consist of (1) a stout copper helmet provided with glass windows, (2) a breast-plate on which the helmet is screwed and secured, and (3) a flexible water-proof dress, which can be connected water-tight with the breast-plate, and covers the whole body except the hands, which project through close-fitting elastic cuffs (Figures 1, 2, and 3). The air is supplied through a flexible rubber pipe strengthened with embedded steel wire and connected with the helmet through a non-return valve. The valve for escape of air is on the right side of the helmet, about the ear-level (Figure 3), and is provided with a weak spring and a screw adjustment for regulating the amount of air in the dress. There is in addition a tap near the front of the helmet as a supplementary means of letting off an excess of air. This tap (familiarly called the "spitcock") is also used by the diver for taking water into his mouth for the purpose of washing down the moisture condensing on the inner surface of the glass window. An extra tap, similarly placed, was used in our experiments for obtaining air-samples from the helmet. In order to enable the diver to sink, front and back weights of 40 lbs. each are attached to the corselet, and each boot is weighted with 16 lbs. of lead on the sole.

Air is forced down to the diver by means of a pump with two double-acting cylinders (Figure 4), the arrangement being such that the air from either one cylinder alone or both cylinders together, can be supplied, according to the depth of the diver, or pair of divers, served by the pump. The internal diameter of each cylinder is 4 inches, and the stroke 7¼ inches, so that, with no leakage or other loss, each cylinder should deliver 0·1 cubic foot of air per revolution of the pump handles, the air being measured at atmospheric pressure. The cylinders are surrounded by a water jacket, to keep them cool.

When a diver goes under water, any air with which his dress is inflated is driven out through the outlet valve by the pressure of the water, so that the dress becomes closely applied to his legs, body, and arms, up to the corselet (Figures 3 and 5). If the valve were kept screwed up so far that the dress remained inflated under water he would not be able to get down. The consequence of the collapse of the dress is that the pressure on all parts of the body below the helmet is greater than in the helmet. If the valve is freely open the excess of pressure on any part of the body will be equal to that of a column of water the height of the valve-outlet above this part.

Thus the external pressure on the chest at the nipple will be about 1 foot of water, or 70 lbs. per square foot, above the pressure in the helmet. As the pressure in the lungs is that of the helmet, the diver will have to expand his lungs against this excess of pressure; and when the experiment is tried the exertion required is found to be very considerable, and breathing is greatly hampered.

In order to experience the effects of varying pressures in the helmet it is merely necessary to alter the height of the valve outlet. A nozzle was therefore substituted for the valve, and a rubber tube of 1 inch diameter and 2 feet long, with a valve on the end, attached to the nozzle. By varying the height of this valve, which was kept freely open, the effects of varying pressure in the helmet were observed by the diver (Dr. Haldane). If the valve was held a few inches above the helmet the excess of pressure on the chest and abdomen was so great that breathing was altogether impossible, owing to the very limited power of the inspiratory muscles. The experiment is a very unpleasant one, and probably not free from risk of hæmorrhage from the lungs or air-passages, or temporary stoppage of the heart. With the valve at the top of the helmet breathing was possible, but was extremely laboured. With the valve at its ordinary level (about opposite the ear), breathing was still laboured, the adverse pressure being specially felt during exertion, or with a short air-supply. With the valve 2 or 3 inches lower, at the level of the upper part of the breast-plate, breathing was much easier. At this height of the valve the helmet and attached weights are just lifted off the shoulders, and the marked relief experienced is probably due largely to the fact that the diver has no longer to inspire from what is practically a small air-space with rigid walls. The smallness of this space makes it impossible for him to inspire freely, except during the actual in-blow from each stroke of the pump. With the valve still lower the helmet is lifted right off the shoulders, and so much air accumulates in the dress that the diver begins to lose his hold on the ground.

Under ordinary conditions an experienced diver adjusts the pressure on his valve in such a way as to ease his breathing as far as possible without endangering his stability, and he may frequently have to adjust the pressure on the valve as he changes the position of his head. If, with the valve comfortably adjusted for the erect position, he stoops down for more than a short time, air accumulates in his dress, and he runs the risk of being "blown up" (*i.e.*, carried to the surface)—a dangerous accident if he is at a considerable depth. In order to stoop or crawl on the bottom he must unscrew his valve, so as to let air escape freely. If his head is nearly as low as his body, as when he is lying or crawling on the bottom, he can, however, breathe quite comfortably with the valve freely open, since the excess of pressure on the chest and abdomen is greatly diminished. This position is the most easy one for a diver.

Bleeding from the nose, &c. is commonly observed with inexperienced divers, and is apparently often due to the difference between the air-pressure and blood-pressure in the walls of the respiratory passages being abnormally increased owing to failure of the diver to keep his valve sufficiently closed, particularly during exertion. An inexperienced diver will, for instance, often struggle up the shotted rope with his valve wide open, and has, consequently, a heavy weight to lift with his arms; whereas an experienced man will screw up his valve sufficiently to take the weight off his arms, and slip up the rope with practically no exertion.

What is the cause of the oppression of breathing which affects divers the more seriously the deeper they go, and which they universally attribute to the increase of pressure? The mere increased absolute pressure can have nothing to do with it. Men in caissons up to depths of 15 fathoms can work quite freely if the ventilation is adequate, and, in fact, are generally believed to work more easily than at normal atmospheric pressure. No oppression of breathing was experienced in the experimental steel chamber by men or animals up to 30 fathoms pressure, or could be observed through the windows in animals up to nearly 40 fathoms pressure; and a careful consideration of the facts pointed, even at the outset of our investigation, towards the conclusion that the cause is not increased pressure of air or water, but increased pressure of the carbonic acid gas (CO_2) present in the air of the helmet.

The means by which breathing is normally regulated has been quite recently elucidated by Haldane and Priestley.[*] The volume of air breathed per minute by an average adult man in a position of perfect rest is about 7·5 litres per minute (at 60° F.), or, roughly, ¼ of a cubic foot. The amount breathed is regulated as follows. At normal atmospheric pressure each person automatically regulates his breathing in such a way that the CO_2 percentage in the alveolar air (air present in the alveoli, or air-cells, of the lungs) contains about 5·6 per cent. of CO_2.[†] The exact percentage varies in different individuals, but is practically constant for the same individual. If the percentage rises, even very slightly, the breathing becomes deeper, so as to effect compensation; if it falls, the breathing is diminished or suspended until it again rises to normal. During even very moderate muscular work the amount of CO_2 given off by the lungs is increased to three or four times the resting normal, and the amount of air breathed is correspondingly increased. With hard work the increase may be twice as great as this. If the air inspired is vitiated by CO_2, the volume breathed is also increased, and in such proportion as, if possible, to keep the alveolar CO_2 percentage nearly normal. Thus, if the air inspired contains 3 per cent. of CO_2, the amount of air breathed will be nearly doubled, since nearly double as much of this vitiated air needs to be inspired in order to keep the alveolar CO_2 percentage normal; and even moderate muscular work in such air will cause great respiratory distress.

When the atmospheric pressure is abnormal the law as just stated ceases to hold, and it is found that what remains constant is not the percentage, but the absolute pressure exercised by the CO_2 in the alveolar air—*i.e.*, the percentage multiplied by the total atmospheric pressure. Thus, to quote an experiment by Haldane and Priestley, it was found that in themselves the mean percentage of CO_2 in the alveolar air was 6·01 per cent. at 765 millimetres (about 30 inches) barometric pressure, and 3·53 per cent. at 1,260 millimetres, while the absolute CO_2 pressures corresponding (allowing for the aqueous vapour in the alveolar air) were 5·64 per cent. and 5·68 per cent. of one atmosphere, or almost exactly the same. Since the work of the Committee began, this law has been verified up to a pressure of 6 atmospheres (corresponding to 28 fathoms of sea-water) by Drs. Hill and Greenwood,[‡] who worked in an experimental steel chamber capable of taking a man in the recumbent position. The same law has also been found by Drs. Boycott and Haldane (unpublished experiments) to hold good down to about two-thirds of an atmosphere. At the latter pressure, therefore, the alveolar air contains as much as $5{\cdot}5 \div \frac{2}{3} = 8{\cdot}25$ per cent. of CO_2 and at the former pressure as little as $5{\cdot}5 \div 6 = 0{\cdot}92$ per cent. CO_2.

To judge from these facts, the effects on a diver of a given percentage of CO_2 in the air of the helmet will vary with the depth of the diver, and the whole of our experiments on diving have confirmed this inference. For instance, as air containing 5 per cent. of CO_2 produces great panting at atmospheric pressure, air containing $\frac{5}{7{\cdot}4} = 0{\cdot}68$ per cent. will produce an equal effect at 35 fathoms, the greatest depth reached by Lieutenant Damant and Mr. Catto. As, however, it was desirable to have some direct quantitative experimental evidence on this point, the following experiment was carried out by Lieutenant Damant on himself and Mr. Catto in the steel chamber. The subject continued to breathe into and out of a large glass bottle until marked panting was produced. This bottle was connected with the graphic recording apparatus devised by Haldane and Priestley,[§] so that the exact increase in the volume of air breathed could be measured near the beginning and end of the experiment, and a sample of the air taken for analysis. The mean results of several experiments were as follows:—

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[*] *Journal of Physiology*, Vol. 32, page 225, 1905.

[†] FitzGerald and Haldane, *Journal of Physiology*, Vol. 32, page 486, 1905.

[‡] *Proceedings of the Royal Society*, Vol. 70, page 455, 1906.

[§] *Loc. cit.*, page 243.

Subject.	Period during which Breathing continued, in Minutes.	Pressure.		CO_2 per Cent. in Air of Bottle at End of Experiments.	Pressure of CO_2 in Bottle in Percentage of one Atmosphere.	Increase in Volume of Air breathed near End of Experiment.
		Pounds per Square Inch above Atmosphere.	Atmospheres absolute.			
Damant - -	3½	0	1	5·70	5·70	×2·4
,, -	4	40	3·7	1·60	5·92	×2·2
Catto - -	3½	0	1	6·22	6·22	×2·9
,, - -	3½	40	3·7	1·64	6·07	×2·3

Owing to to the limited capacity of the bottle, and consequent shortness of each experiment, the results are not strictly accurate; but they leave no doubt that the effect of CO_2 on the breathing depends on its pressure, and not merely on its percentage.

A corollary of fundamental importance in diving follows from this law. It is that *whatever the pressure a diver is under, he requires the same volume of air, measured at that pressure.* In other words, his minimum supply of air, measured on the surface at ordinary atmospheric pressure, must increase in direct proportion to the absolute pressure he is under. A diver at 210 feet, or 7·4 atmospheres absolute pressure, will thus need 7·4 times as much air, measured either by weight, or by volume at ordinary atmospheric pressure, as he would need at surface.

Average atmospheric pressure at sea-level (760 millimeters, or nearly 30 inches of mercury) is equivalent approximately to the pressure of 34 feet of fresh water, or 33 feet of sea-water, hence the following table represents the increased air supply needed at various depths of sea-water, by a diver, as compared with what he would need at surface level:—

At	2	atmospheres, or	33	feet, or	5½	fathoms	the air supply must be increased to	double.
At	3	,,	66	,,	11	,,	,,	treble.
At	4	,,	99	,,	16½	,,	,,	4 times.
At	5	,,	132	,,	22	,,	,,	5 ,,
At	6	,,	165	,,	27½	,,	,,	6 ,,
At	7	,,	198	,,	33	,,	,,	7 ,,
At	8	,,	231	,,	38½	,,	,,	8 ,,
At	9	,,	264	,,	44	,,	,,	9 ,,
At	10	,,	297	,,	49½	,,	,,	10 ,,

It is evident also that the work expended in pumping an adequate supply of air increases very rapidly with increase in depth, even if no extra leakage from the pumps be allowed for, since not only the resistance to pumping, but also the quantity of air needed, increases in proportion to the pressure. From the practical standpoint this is a most important consideration.

Since a diver not only inspires from, but expires into the air in his helmet, he must re-breathe to a greater or less extent the CO_2 which he produces; and if he does so to a considerable extent he will evidently need to breathe much more deeply and frequently than would otherwise be the case. Since, moreover, he has also to breathe against greater or less pressure from the causes already explained, he will not only be much inconvenienced, but, as shown below, his CO_2-production will be increased by the great exertion of breathing, and this will still further increase his distress. The consequent accumulation of CO_2 in the helmet may lead to loss of consciousness, particularly if the respiratory centre becomes partly exhausted, as may easily happen. Inexperienced divers are not infrequently pulled up in an unconscious state, apparently from this cause.

In order to obtain further information as to the effects of CO_2-pressure in the air of the helmet, and the adequacy or otherwise of the air-supply under ordinary conditions in diving, it was evidently necessary to obtain samples of air from the helmet for analysis. These were obtained through the supplementary outlet tap ("spitcock") at the side of the helmet in front, at about the mouth-level.

Most of the samples were collected in receivers of stout glass (Figures 6, 7, 8) provided with three-way taps at each end. Since the samples from deep water had often to be taken in complete darkness, each receiver was marked by the knobs of glass shown in the figure. These could easily be felt and counted by the diver. The knobs shown on the taps indicated whether the latter were open or closed. The receivers were filled with water before use. The method of taking the samples is shown in the figure, the receiver being held above the level of the outlet valve, so that the air should blow out freely. In the case of samples taken from very deep water the excess of pressure was relieved when the diver was half-way up, as there was otherwise a risk of the receivers exploding or the taps being blown out.

When samples had to be taken with as little delay as possible, as during work experiments, ordinary bottles of about 70 cc. (2 ounces) capacity were used, the open bottles being simply inverted over the tap. Each bottle was provided with a perforated cork, through which passed a short piece of glass tube, to which was attached a piece of rubber tube closed at the end by a glass stopper (Figure 9). Between the stopper and glass tube there was a longitudinal slit in the rubber tubing. This acted as a non-return valve, allowing the excess of air to escape as the diver ascended. When the diver reached the surface the glass stopper was pushed down so as to make the closure quite secure. In a few cases ordinary bottles with greased glass stoppers were used, the stopper being secured by an elastic band which allowed the excess of air to blow out as the diver ascended. At the surface the stopper was made tight by turning it round and pushing it well in.

For the analyses an easily portable apparatus (Figure 8) was specially designed by Dr. Haldane, who described it in the *Journal of Hygiene*, Vol. 6, page 74, 1906. It gives results accurate to within ·01 per cent., 10 cc. of air being needed for each analysis. The method of transferring the air from the glass receivers or bottles into the gas-burette is shown in Figure 8, and was the same as that described by Dr. Haldane in *The Investigation of Mine Air*, Griffin & Co., 1905. In using the gas-analysis apparatus on board ship some difficulty arose owing to rolling, and consequent unsteadiness of the mercury level in the burette. This difficulty was overcome by having two screw-clips close to the gas-burette on the rubber tube connecting it with the mercury reservoir. Before each reading one of these was screwed up tight, so as to steady the mercury; and the level was accurately adjusted by tightening or loosening the other clip.

In interpreting the analyses it is necessary, as already explained, to bear in mind not merely the percentages, but the pressures of the gases present in the helmet, since their physiological effects depend upon their pressures. As regards the most important gas, CO_2, it was found by Haldane and Priestley[*] that with a pressure of 2 per cent. of an atmosphere the amount of fresh air taken into the air cells of the lungs was increased about 50 per cent.; with 3 per cent. about 100 per cent.; with 4 per cent. about 200 per cent.; with 5 per cent. about 300 per cent.; and with 6 per cent. about 500 per cent. With the latter pressure panting is severe, whereas with 3 per cent. the increased depth of breathing might easily escape notice except during muscular work, which would cause about 100 per cent. more panting than usual, the effects of the CO_2 on the breathing being multiplied by, and not merely added to, the effects of the work. With more than 6 per cent. the distress is very great, and headache is often produced in a short time. With more than about 10 per cent. there is an increasing tendency to loss of consciousness, accompanied, however, by no immediate danger to life; and even 25 per cent. of CO_2 takes a long time to produce death in animals. A mixture of about 15 or 20 per cent. of CO_2 with air is reported to have been tried as an anæsthetic before chloroform, &c., were adopted. When a diver's breathing is greatly hampered, and his CO_2 production is increased by struggling, the anæsthetic effects of CO_2 are, owing to exhaustion of his breathing powers, probably produced by a considerably less pressure of CO_2 than during rest with the breathing free.

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[*] *Loc. cit.*, page 249.

Deficiency of oxygen has much more formidable and dangerous effects than excess of CO_2; but a diver using the ordinary apparatus is never in danger from this cause. The effects, if any, of oxygen, like those of CO_2, depend upon its pressure, hence the deeper a diver goes the more abundant is his supply of oxygen. Even at the surface a man breathing in a confined space, such as a diver's helmet, feels the effect of CO_2 severely before he is in any danger from want of oxygen; and a diver 5 fathoms under water would certainly become unconscious from excessive pressure of CO_2 long before he was affected by deficiency of oxygen. A diver may have to fear the effects of excess of oxygen pressure, but only at depths greater than have hitherto been accessible, as will be shown in Part III. In the samples taken the oxygen percentages have been determined merely as a check upon the CO_2 percentages.

When the air supply to a diver is definitely known his production of CO_2 per minute can be calculated from the analyses of the helmet air, if we assume that, as will be shown below to be approximately true, the composition of the sample is the same as that of the air leaving the helmet. This calculation, which is a very useful one, has therefore been made in connection with the analyses, whenever the delivery of the pumps, allowing for leakage, was known.

The following analyses of air from the helmet were made with a view to determining the effects of adverse pressure in breathing on the CO_2 production of a diver. The samples were obtained in the experimental diving tank, Dr. Haldane being the subject. The samples in each pair were taken after 3 and 5 minutes of ventilation, at as nearly as possible a constant rate of 12 revolutions of the single pump, or 1·2 cubic feet of air, per minute, about an hour being occupied for the whole series. The movable experimental valve, described above, was attached to the helmet :—

	—	Percentage of CO_2.		Pressure of CO_2 in Percentages of Atmosphere.	Production of CO_2 in Cubic Feet per Minute.
1	Standing on the platform above water in the diving dress, with air escaping freely from the valve. Dress only slightly distended. Breast and back weights off. Stood 5 minutes before first sample taken - - - -	A 1·95 B 1·61	1·78	1·78	·021
2	Kneeling on bottom, helmet 6 feet below surface. Experimental valve at level of top of breast-plate. Valve open freely. Breathing easy.	C 2·54 D 2·73	2·63	3·16	·031
3	Same as last, but experimental valve at level of ordinary valve (height of ear). Breathing laboured - - - - -	E 3·40 F 3·86	3·63	4·36	·043
4	Same as last, but experimental valve at top of helmet. Caused so much distress that the two samples could not be taken successively, and the CO_2 had probably not reached its maximum percentage - - - - -	G 4·20 H 3·91	4·05	4·86	·048+
5	Same as No. 2, but pump now at six revolutions. Caused very great distress and samples had to be taken too soon, so that CO_2 had certainly not reached its maximum - - -	J 6·12 K 5·55	5·83	7·00	?

These results are in many ways instructive. During complete rest in an easy position the CO_2-production of Dr. Haldane, which has been often measured, varies from about ·010 to ·012 cubic feet per minute (measured at about 60° F.). Yet in the diving dress, during rest under water with the breathing easy (No. 2), the CO_2-production was nearly thrice as great,[*] and was four times as great with the valve freely open in its ordinary position. The strain of the unaccustomed position under water thus caused

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[*] This was of course chiefly due to the want of experience of the diver. During rest in an easy position in the tank Lieutenant Damant and Mr. Catto only produced about 0·14 cubic feet of CO_2 per minute, and often less than this. Experiments No. 2 and 3 were repeated with Mr. Catto as subject and an abundant air supply (2 cubic feet per minute). His CO_2-production in a perfectly easy position, with the valve screwed up so as to completely ease the breathing, was ·010 cubic feet per minute, and with the valve freely open ·014 cubic feet per minute, or 40 per cent. more.

a great increase in the CO_2-production, the latter being still further raised to the extent of about 40 per cent. by the extra breathing work with the valve open at its ordinary level. It should, however, be borne in mind that about half this extra work must have been due to the inadequate air-supply, since in No. 3 the CO_2 pressure had reached 4·36 per cent. of an atmosphere. Failure to manage the valve properly thus produces a vicious circle of causes of discomfort to a diver. In No. 5 the sense of pressure, distress, and disablement, for all practical purposes, was similar to that produced in divers in very deep water with the ordinary inadequate air-supply.

The want of correspondence between the calculated CO_2-production during rest, standing in the diving dress, and in an ordinary comfortable position, at first aroused the suspicion that the samples from the side tap of the helmet might, owing to imperfect mixture of the air inside the helmet, contain more CO_2 than the air escaping from the outlet valve. To test this point, arrangements were made to take samples as nearly as possible simultaneously from the side tap and the internal opening of the outlet valve. A helmet with two side taps was used, one of these taps being connected by a narrow tube inside the helmet with the opening of the outlet valve. The experiments were made in the gas-engine cooling tank at the Physiological Laboratory, Oxford. The results were as follows, the ventilation being, as before, at as nearly as possible 12 revolutions of the single pump, or 1·2 cubic feet, per minute :—

No. of Experiment.	Position of Diver.	CO_2 per Cent. at Mouth Level.	CO_2 per Cent. at Exhaust Valve Level.
1	On surface outside tank - - -	1·16	1·52
2	" " - - -	1·56	1·40
3	In tank, valve just below surface - -	1·95	2·07
4	" " " - -	1·41	1·44
5	In tank, valve well below surface - -	1·41	1·02
6	" " " - -	1·12	·95
	Mean - - - -	1·45	1·40

It will be seen that although there were sometimes differences in one direction or the other between the two samples in each pair, due in part, probably, to their not being quite simultaneously taken, there was practically no average difference; so that the mixture in the helmet is fairly complete, there being no short-circuit of fresh air from the inlet to the outlet valve.

In the case of the last pair of samples, the diver (Dr. Haldane) took special care to get into a perfectly comfortable position in the tank, with the valve well screwed up, so as to make the breathing perfectly easy. The average percentage of CO_2 in the two samples was now only 1·03, corresponding to a production of CO_2 of ·012 cubic feet per minute—a normal amount for complete rest in his case.

A large number of samples have been collected under ordinary conditions of diving, during both rest and work. The results are shown in the accompanying table. In many of the earlier samples the leakage of the pumps used was not measured at the time, and owing to the leakage varying from day to day, could not be accurately estimated, so that the CO_2-production of the diver cannot be stated. The samples are arranged in order of the depth at which they were obtained. In collecting them, care was taken, so far as possible, to keep the pump working at a constant speed, and the diver in a constant state of rest or work, for 2 or 3 minutes previously.

Diver.	Depth to Helmet.		Absolute Pressure in Atmospheres (33 Feet to One Atmosphere).	Revolutions of Pump per Minute.	No. of Cylinders in use.	Air Supply in Cubic Feet per Minute.	CO_2 per Cent. in Sample.	Deficiency of Oxygen per Cent. in Sample.	CO_2 Pressure in per Cent. of One Atmosphere.	CO_2-Production of Diver in Cubic Feet per Minute.	Remarks.
	Feet.	Fathoms.									
J. S. H. - -	1	1/6	1·03	12	1	1·2	1·03	—	1·06	·012	Complete rest in easiest position in gas-engine tank at Oxford.
C. - -	3	1/2	1·09	24	1	2·4	·76	·94	·82	·017	Rest in diving tank.
C. - - -	3	1/2	1·09	12	1	1·2	1·76	1·89	1·91	·020	„ „
C. - -	3	1/2	1·09	14	1	1·4	2·10	2·53	2·28	·028	After walking a short way in tank.
C. - - -	3	1/2	1·09	13	1	1·3	2·82	3·35	3·08	·036	„ „ „
C. - -	3	1/2	1·09	12	1	1·2	3·83	3·60	4·17	·045	At rest after walking until much exhaustion in tank.
C. - - -	3	1/2	1·09	12	1	1·2	4·36	3·40	4·75	·051	Whilst walking in tank.
J. S. H. - -	3	1/2	1·09	9	1	·9	3·82	4·95	4·16	·034	Walking slowly about tank.
J. S. H. - -	3	1/2	1·09	9	1	·9	3·50	4·91	3·81	·031	At rest in tank; valve wide open.
J. S. H. - -	6	1	1·18	12	1	1·2	2·54	—	2·99	·030	At rest in tank.
J. S. H. - -	6	1	1·18	12	1	1·2	2·73	—	3·32	·032	„ „
D. - -	6	1	1·18	24	2	4·21	·42	·45	·49	·015	„ „
D. - - -	6	1	1·18	24	2	4·21	·34	·45	·40	·013	„ „
D. - -	6	1	1·18	26	2	4·56	1·62	1·66	1·92	·072	Walking for 20th time round tank.
C. - - -	6	1	1·18	32	2	5·72	·28	·28	·33	·013	Rest in tank.
C. - -	6	1	1·18	32	2	5·72	·25	·35	·41	·012	„ „
C. - - -	6	1	1·18	28	2	5·00	·66	·78	·92	·031	Walking for 20th time round tank.
C. - -	6	1	1·18	30	2	5·26	·25	·19	·29	·011	Rest in tank.
C. - - -	6	1	1·18	30	2	5·26	·16	·18	·18	·006	„ „
C. - -	6	1	1·18	23	2	4·03	1·34	1·39	1·58	·054	Walking for 20th time round tank.
C. - - -	6	1	1·18	23	2	4·03	·85	·93	1·09	·033	„ „ „
C. - -	21	3½	1·63	30	1	2·7 (about)	·63	—	1·03	·016	Rest, sitting on bottom.
C. - - -	21	3½	1·63	30	1	2·7 „	1·30	—	2·13	·034	Work, after lifting 56-lb. shot 3 feet 36 times in 13½ minutes.
1st Class P.O., W. -	21	3½	1·63	30	1	2·7 „	·38	·46	·60	·009	Rest, sitting on bottom.
W. - -	21	3½	1·63	30	1	2·7 „	1·14	1·24	1·87	·029	Work, after lifting 56-lb. shot 3 feet 28 times in 4½ minutes.
C. - - -	25	4 1/6	1·75	28	1	2·38	·5	·58	·87	·011	At rest kneeling on bottom.
C. - -	25	4 1/6	1·75	28	1	2·38	1·54	—	2·69	·035	Walking about as in ordinary work.
C. - - -	25	4 1/6	1·75	28	1	2·38	1·94	2·15	3·39	·045	„ „ „
D. - -	25	4 1/6	1·75	28	1	2·38	·7	·82	1·22	·015	Rest.
D. - - -	25	4 1/6	1·75	28	1	2·38	2·63	3·31	4·60	·061	Working, ordinary exertion.
D. - -	25	4 1/6	1·75	28	1	2·38	2·52	3·22	4·41	·059	„ „
C. - - -	25	4 1/6	1·75	29	4	—	·29	—	·50	—	Resting.

Diver.	Depth to Helmet.		Absolute Pressure in Atmospheres (33 Feet to One Atmosphere).	Revolutions of Pump per Minute.	No. of Cylinders in use.	Air Supply in Cubic Feet per Minute.	CO_2 per Cent. in Sample.	Deficiency of Oxygen per Cent. in Sample.	CO_2 Pressure in per Cent. of One Atmosphere.	CO_2-Production of Diver in Cubic Feet per Minute.	Remarks.
	Feet.	Fathoms.									
1st Class P.O., H.	25	4⅙	1·75	26	4	—	·39	—	·68	—	Resting.
C.	25	4⅙	1·75	29	4	—	·24	·18	·42	—	,,
1st Class P.O., H.	25	4⅙	1·75	26	4	—	·44	—	·77	—	,,
D.	34	5⅔	2·00	28	1	2·36	1·00	·74	2·00	·022	At rest.
D.	34	5⅔	2·00	32	1	2·66	2·00	2·44	4·00	·052	Work, ordinary exertion.
D.	34	5⅔	2·00	34	1	2·83	2·35	2·52	4·70	·065	,, ,,
D.	40	6⅔	2·2	21	2	3·50	1·00	—	4·40	·085	,, ,,
D.	40	6⅔	2·2	23	2	3·85	·51	—	1·12	·018	Rest.
D.	40	6⅔	2·2	21	2	3·50	1·58	—	3·50	·054	Work, ordinary exertion.
C.	40	6⅔	2·2	17	2	2·83	·45	—	·99	·011	Rest.
C.	40	6⅔	2·2	23	2	3·84	·81	—	1·78	·029	Work, ordinary exertion.
C.	40	6⅔	2·2	17	2	2·83	·83	—	1·82	·022	,, ,,
C.	42	7	2·3	24	1	1·93	·88	·97	2·02	·015	Rest.
C.	42	7	2·3	27	1	2·16	1·72	1·97	3·95	·036	Work, ordinary exertion.
C.	42	7	2·3	29	1	2·34	2·02	2·13	4·65	·046	,, ,,
C.	42	7	2·3	28	1	2·55	·79	·45	1·82	·019	Rest.
C.	42	7	2·3	28	1	2·55	3·2	2·82	7·42	·079	Work, diver exhausted by sticking in mud.
D.	42	7	2·3	28	1	2·38	·4	·50	·92	·008	Rest.
D.	42	7	2·3	28	1	2·36	2·08	2·47	4·78	·048	Work, ordinary exertion.
D.	50	8⅓	2·5	20	2	3·18	1·47	—	3·67	·045	,, ,,
D.	50	8⅓	2·5	22½	2	3·57	·54	—	1·35	·018	Rest.
C.	52	8⅔	2·6	24	2	3·81	·48	—	1·27	·017	,,
C.	52	8⅔	2·6	24	2	3·81	·64	—	1·66	·023	Work, ordinary exertion.
C.	52	8⅔	2·6	24	2	3·81	·89	—	2·30	·032	,, ,,
C.	55	9⅙	2·7	18½	2	2·89	·57	—	1·78	·016	Rest.
C.	55	9⅙	2·7	18	2	2·82	·87	—	2·35	·023	Work, ordinary exertion.
C.	55	9⅙	2·7	16	2	2·50	1·15	—	3·10	·027	,, ,,
D.	60	10	2·8	17½	2	2·73	1·07	—	2·99	·027	Rest.
D.	60	10	2·8	17	2	2·66	1·69	—	4·74	·042	Work, ordinary exertion.
D.	60	10	2·8	16½	2	2·53	·89	—	2·49	·022	Rest.
D.	63	10½	2·9	17	2	2·69	1·77	—	5·14	·046	Work, ordinary exertion.
D.	63	10½	2·9	18	2	2·96	1·42	—	4·12	·042	,, ,,
D.	63	10½	2·9	26	1	2·17	·92	1·05	2·67	·019	Rest.

D. - - -	63	10½	2·9	26	1	2·17	2·03	2·57	5·89	·043	Work, ordinary exertion.
D. - - -	63	10½	2·9	26	1	2·17	2·36	2·87	6·85	·050	" "
D. - - -	63	10½	2·9	23	2	3·83	·5	·63	1·45	·018	Rest.
D. - - -	63	10½	2·9	23	2	3·83	1·06	1·33	3·03	·039	Work, ordinary exertion.
C. - - -	63	10½	2·9	23	2	3·57	·56	·52	1·62	·019	Rest.
C. - - -	63	10½	2·9	23	2	3·58	·38	·75	1·68	·016	"
C. - - -	63	10½	2·9	23	2	3·58	·98	1·07	2·84	·029	Work, ordinary exertion.
C. - - -	63	10½	2·9	25½	2	3·81	·77	—	2·23	·025	" "
C. - - -	63	10½	2·9	25	1	1·97	·93	·96	2·69	·017	Rest.
C. - - -	63	10½	2·9	25	1	1·97	1·48	1·81	4·29	·028	Work, ordinary exertion.
C. - - -	68	11⅓	3·06	30	4	8·0 (about)	·23	—	·70	·016	Rest, sitting on bottom.
C. - - -	68	11⅓	3·06	30	4	8·0 (about)	·41	—	1·25	·030	Work, after lifting 56 lbs. 4 feet 38 times in 14 minutes 10 seconds.
H. - - -	68	11⅓	3·06	30	4	8·0 (about)	·24	—	·73	·019	Rest, sitting on bottom.
H. - - -	68	11⅓	3·06	30	4	8·0 (about)	·42	—	1·29	·031	Work, after lifting 56 lbs. 4 feet 40 times in 27½ minutes.
D. - - -	70	11⅔	3·1	28	1	2·24	·86	·92	2·66	·018	Rest.
D. - - -	70	11⅔	3·1	29	1	2·32	1·90	2·63	5·89	·042	Work, ordinary exertion.
D. - - -	70	11⅔	3·1	26	1	2·08	2·00	—	6·20	·040	" "
C. - - -	70	11⅔	3·1	29	1	—	1·08	1·27	3·35	—	Rest.
C. - - -	70	11⅔	3·1	29	1	—	·80	1·15	2·48	—	"
H. - - -	70	11⅔	3·12	30	1	2·0 (about)	·84	—	2·62	·016	Rest, sitting on bottom.
H. - - -	70	11⅔	3·12	30	1	2·0 (about)	1·47	—	4·59	·028	Work, after lifting 56 lbs. 6 feet 6 times 5½ minutes.
Carpenter's Mate, H.	72	12	3·2	32	1	—	·95	1·00	3·04	—	Rest.
" " H.	72	12	3·2	25	1	—	1·08	1·29	3·32	—	"
1st Class P.O., S. -	72	12	3·2	28	1	—	1·78	—	5·77	—	"
" " S. -	72	12	3·2	28	1	—	1·48	—	4·75	—	"
C. - - -	74	12⅓	3·2	29	1	2·41	1·66	—	5·31	·039	Work, ordinary exertion.
C. - - -	74	12⅓	3·2	28½	1	2·12	1·49	—	4·78	·030	" "
C. - - -	75	12½	3·2	25	—	—	1·08	—	3·32	—	Rest.
C. - - -	75	12½	3·2	29	1	—	1·15	—	3·50	—	"
C. - - -	75	12½	3·2	29	1	—	1·03	—	3·14	—	"
C. - - -	75	12½	3·27	30	1	2·0 (about)	·92	—	3·01	·017	Rest, sitting on bottom.
C. - - -	75	12½	3·27	30	1	2·0 (about)	1·60	—	5·24	·031	Work, after lifting 56 lbs. 3¾ feet 11 times in 5 minutes.
C. - - -	76	12⅔	3·3	27	1	—	1·20	—	3·96	—	Rest.
C. - - -	76	12⅔	3·3	27	1	—	1·05	—	3·46	—	"
C. - - -	84	14	3·5	27	1	—	1·58	1·50	5·54	—	Rest, kneeling on bottom.
C. - - -	84	14	3·5	27	1	—	1·62	1·70	5·68	—	" " "
C. - - -	84	14	3·5	27	1	—	1·54	1·65	5·40	—	" " "
D. - - -	90	15	3·7	16	4	4·57	·78	·82	3·67	·033	Rest, heavy tide running.
D. - - -	90	15	3·7	16½	4	4·72	1·35	1·86	5·00	·062	Work, heavy tide running.

Diver.	Depth to Helmet.		Absolute Pressure in Atmospheres (33 Feet to One Atmosphere).	Revolutions of Pump per Minute.	No. of Cylinders in use.	Air Supply in Cubic Feet per Minute.	CO_2 per Cent. in Sample.	Deficiency of Oxygen per Cent. in Sample.	CO_2-Pressure in per Cent. of One Atmosphere.	CO_2-Production of Diver in Cubic Feet per Minute.	Remarks.
	Feet.	Fathoms.									
C.	92	15⅓	3·8	18	4	5·15	·48	—	1·84	·023	Rest.
C.	92	15⅓	3·8	16½	4	4·72	·49	—	1·86	·021	"
C.	92	15⅓	3·8	17	4	4·86	·85	—	3·23	·041	Work, ordinary exertion.
C.	104	17⅓	4·1	25	4	3·80	·56	·73	2·39	·020	Rest.
C.	104	17⅓	4·1	25	4	3·80	·90	·80	3·69	·033	Work, ordinary exertion.
C.	104	17⅓	4·1	22	2	—	1·16	—	4·75	—	Resting.
1st Class P.O., W.	105	17½	4·1	27	1	—	2·44	—	10·00	—	Resting with one cylinder; was much exhausted, and could hardly take sample.
W.	105	17½	4·1	32	2	—	1·54	1·73	6·32	—	Rest, recovering after last sample.
W.	105	17½	4·1	32	2	—	1·78	—	7·30	—	" "
W.	106	17⅔	4·1	26	1	—	1·07	1·09	4·15	—	Rest.
C.	106	17⅔	4·1	19	2	2·72	·9	—	3·78	·023	"
C.	106	17⅔	4·1	23	2	3·30	·98	—	4·12	·031	Work.
C.	106	17⅔	4·1	21	2	3·00	·94	·97	3·94	·027	"
C.	106	17⅔	4·1	18	4	5·07	·58	—	2·44	·028	"
C.	106	17⅔	4·1	16½	4	4·65	·5	—	2·10	·026	"
C.	106	17⅔	4·1	20	4	5·34	·35	—	1·47	·017	Rest.
C.	106	17⅔	4·1	19	4	5·07	·60	—	2·52	·030	Work.
C.	106	17⅔	4·1	18½	4	4·93	·50	—	2·10	·023	"
D.	106	17⅔	4·1	22	2	3·13	·60	—	2·52	·017	Rest.
D.	106	17⅔	4·1	20	2	2·86	1·34	—	5·63	·037	Work.
D.	106	17⅔	4·1	20	2	2·86	1·58	—	6·64	·044	"

B. - - -	106	17⅔	4·1	20	4	5·34	·41	—	1·74	·020	Rest.
D. - - -	106	17⅔	4·1	19½	4	5·20	1·02	—	4·28	·054	Work.
1st Class P.O., W. -	108	18	4·2	23	4	—	·41	—	1·72	—	Rest.
C. - - -	110	18⅓	4·3	20	4	—	·45	—	1·94	—	,,
1st Class P.O., S. -	110	18⅓	4·3	20	2	—	·63	—	2·70	—	,,
Carpenter's Mate, H.	110	18⅓	4·3	21	3	—	·52	—	2·24	—	,,
C. - - -	112	18⅔	4·3	32	2	—	·83	—	3·36	—	,,
1st Class P.O., W. -	115	19⅙	4·5	16	1	—	1·80	1·86	8·10	—	,,
W. - - -	115	19⅙	4·5	40	2	—	·51	·35	2·29	—	,,
D. - - -	139	23⅙	5·3	26	4	8·5	·18	·31	0·95	·013	Rest. Sitting on shot.
D. - - -	139	23⅙	5·3	26	4	8·5	·73	·92	3·87	·059	Work. Just after five lifts of 56-lb. weight, 3 feet each.
D. - - -	139	23⅙	5·3	24	4	7·8	·81	·68	4·28	·061	Work. Just after 18 more lifts of 3 feet each. Exhausted.
C. - - -	142	23⅔	5·3	30	4	9·8	·30	·42	1·60	·026	Rest.
C. - - -	142	23⅔	5·3	30	4	9·8	·70	·81	3·73	·066	Work. Just after four lifts of 56-lb. weight, 5 feet each lift.
C. - - -	142	23⅔	5·3	30	4	9·8	·71	·81	3·78	·067	Work. Just after seven more lifts of 5 feet each.
D. - - -	173	28⅚	6·2	30	4	8·24	·46	·51	2·85	·035	Rest. Distinct tide.
D. - - -	173	28⅚	6·2	30	4	8·24	·39	·55	2·41	·029	,, ,,
D. - - -	173	28⅚	6·2	30	4	8·24	·36	·60	2·05	·027	,, ,,
D. - - -	186	31	6·6	30	4	8·85	·32	·20	2·11	·025	Rest.
D. - - -	186	31	6·6	30	4	8·85	·50	·64	3·30	·041	,, (?)
D. - - -	210	35	7·3	30	6	12·24	·14	·14	1·02	·013	Rest, sitting on shot of shot rope.
C. - - -	210	35	7·3	24	6	9·80	·53	·70	3·86	·049	Rest, but had just walked the length of the distance line.

Attention may first be drawn to the column showing the pressure of CO_2 in the air of the helmet. It will be noticed that this varied from 0·18 to 10·0 per cent. of an atmosphere. The sample showing the latter very high pressure was taken under great difficulties by Instructor Watkins just before signalling for more air, and when he was probably on the verge of losing consciousness. As he was resting on the bottom his distress was entirely due to the inadequate air-supply, which was probably about 1·6 cubic feet per minute measured at surface, or less than 0·4 cubic feet per minute measured as it reached him. From the statements of the divers the general inference could be drawn that marked inconvenience and inability to continue any considerable exertion were experienced as soon as the CO_2-pressure began to exceed about 4 per cent. of an atmosphere. Thus at a depth of 23½ fathoms, or 139 feet, and a CO_2-pressure of 4·28 per cent., Lieutenant Damant was unable to continue for more than 8 minutes the heavy exertion of pulling a rope passing through three blocks, so as to lift a 56-lb weight about 9 feet per minute. On the other hand, with the CO_2-pressure well under 3 per cent., heavy exertions, such as walking smartly in the tank, or on the bottom, could be continued for long periods. Even at the extreme depth of 35 fathoms both divers were perfectly comfortable with a CO_2-pressure of less than 4 per cent.

The column showing the CO_2-production per minute is of much importance, as furnishing data from which it is possible to calculate easily the supply of air needed by a diver, taking into account also his depth. During rest the average production of CO_2 by Lieutenant Damant was ·022 cubic feet per minute on the sea-bottom, and ·014 cubic feet in the tank, where the conditions were more favourable from absence of tide. For Mr. Catto the figures were ·016 on the sea-bottom, and ·013 in the tank. As both divers are spare and not tall, weighing only about 11 stone, their normal average CO_2-production, during complete rest, is probably not more than ·01 cubic feet, so that during rest on the sea-bottom their average CO_2-production was about double the true resting value, and sometimes, in consequence of the exertion required to keep steady with a tide running, even three or four times the true resting value. Of special interest is the CO_2-production of Lieutenant Damant at 35 fathoms, the greatest depth reached. Sitting quietly on the weight at the end of the shot-rope, with no tide running, his CO_2-production was only ·013 cubic feet per minute, which was the same as in the tank at one fathom or on the sea-bottom under the same conditions at 23 fathoms. The oxygen pressure was 7·3 times the normal, or 153 per cent. of an atmosphere so, that he was breathing 7·3 time as much oxygen as usual, but the oxidation processes in his body were not increased.

During work the CO_2-production was, of course, always much higher than during rest. The greatest amount (·079 cubic feet per minute) was produced by Mr. Catto, during struggles to free himself from the mud, in which he had stuck at a depth of 7 fathoms. The air supply was rather short, and the CO_2-pressure, when this sample was taken, was 7·42 per cent. of an atmosphere, the diver being naturally much exhausted by his two-fold struggle with the mud and the air. The production of CO_2 was about eight times the true resting value. Very nearly as high a CO_2-production (·072 cubic feet) was observed in the case of Lieutenant Damant, while he was walking vigorously round the tank. He had, however, an abundant air-supply, and was not distressed, the CO_2-pressure in the helmet being only 1·92 per cent. For ordinary fairly hard work the amounts more commonly obtained were ·04 to ·06, or about two to three times the average amount during rest on the sea-bottom. To take a good example of hard work Lieutenant Damant produced ·013 cubic feet per minute during rest at 23 fathoms, and ·059 to ·061 while pulling vigorously on a rope.

It is quite evident from the data obtained that in calculating the proper air-supply for a diver allowance must be made for what, under any conditions, would be regarded as fairly hard work. Even if the work he has to do would be very moderate if done on the surface, he may have in addition to struggle hard with tide and mud, or when he is foul, often in complete darkness; and if an exhausting struggle for breath, in consequence of a high CO_2-pressure in the helmet, is added to his other troubles, he may easily be incapacitated for his work; or his life may be endangered if his mind becomes confused, since he might blow himself suddenly to surface by failure to manage his valve, or in certain situations might fall and be fatally injured by the squeeze due to the suddenly increased pressure.

Since a diver resting on the bottom usually produces, to judge from our experiments, about ·019 cubic feet per minute, he would need, during rest at atmospheric pressure, just below surface, $·019 \times \frac{100}{3} = ·63$ cubic feet per minute, in order to keep the CO_2-percentage down to 3 per cent. During moderately hard work he produces about ·045 cubic feet of CO_2 per minute. Hence we may conclude that a diver at work ought not to have less than $·045 \times \frac{100}{3} = 1·5$ cubic feet per minute. For the reasons already explained, he should have this *volume* of air at whatever pressure he may be. Hence he will need, if the air be measured at atmospheric pressure, the following air supply:—

Depth.	Cubic Feet per Minute.
Surface	1·5
5½ fathoms	3
11 ,,	4·5
16½ ,,	6
22 ,,	7·5
27½ ,,	9
33 ,,	10·5
38½ ,,	12
44 ,,	13·5
49½ ,,	15

An ampler air-supply would doubtless be of much advantage during hard work, since a pressure exceeding 3 per cent. of CO_2 will have, as already seen, a very marked effect upon the breathing, and will thus limit the power of doing hard work. The diver will, however, at least be spared the severe struggles for breath and dangers of losing consciousness, which are so common under present conditions at considerable depths or under conditions which necessitate much exertion.

It is perhaps scarcely necessary to allude to the imaginary dangers which are popularly supposed to attend the breathing of air vitiated by respiration to such an extent as 3 per cent. of CO_2. Any danger from the supposed "organic matter" in such air is certainly non-existent. In the case of the Rotherhithe tunnel, at present being constructed under the Thames, the London County Council requires that the proportion of CO_2 in the compressed air in which the men work should not exceed ·08 per cent. Whatever the reason may be for this extremely costly requirement, it is certain that neither CO_2 nor "organic matter" from respiration would have any deleterious effect unless this proportion were very largely exceeded; and although our standard of ventilation permits of 150 times as much "respiratory impurity" as is commonly alleged to be injurious, we have no misgivings whatsoever as to the "organic matter."

In order to attain to a given standard of ventilation it is evidently necessary to keep the pump running at a certain rate; and in view of the probability that the oppression experienced by divers in deep water is due to increased pressure of CO_2 from inadequate ventilation, the first thing done was to test the pump which was to be employed in the early experiments in the tank. Unfortunately, as matters turned out, this particular pump was new, and phenomenally good. It delivered at the time exactly the quantity of air (·10 cubic feet per revolution for each cylinder) calculated from the diameter of the cylinders and stroke of the pistons; and at a pressure of 140 feet of water the delivery was still within 12 per cent. of this amount. As a consequence, it was somewhat rashly assumed that other pumps, if oiled and cared for in accordance with the Service directions, would give about equally good results. The results of analyses of air-samples from deep water soon, however, aroused suspicions. Thus, to take an instance, three samples collected by Mr. Catto during rest at 14 fathoms, with the single pump at 27 revolutions per minute, gave respectively 1·58, 1·62, and 1·54 per cent. of CO_2 (corresponding to the high pressures of 5·54, 5·68, and 5·40 per cent.

of an atmosphere of CO_2); whereas, to judge from samples obtained by the same diver while at rest in the tank, not more than 0·8 per cent. CO_2 ought to have been present if the pump was delivering about 2·7 cubic feet of air per minute, as it would have been doing had it been tight. Other results were still more anomalous—for example, the intense distress (with a pressure of 10 per cent. of an atmosphere of CO_2) caused to Instructor Watkins at 17½ fathoms by a ventilation, during rest, of 27 revolutions of the single pump per minute. It was therefore resolved to test all the pumps used in these dives; and subsequently a number of other pumps, from various vessels at Portsmouth, were examined.

For testing a diving pump the only process at present in use is to attach a length of pipe, blank-flanged at the far end, to the pump, and then pump air up to a considerable pressure into this pipe, and watch the gauge after stopping the pump. If the pressure only falls slowly, if at all, the pump is supposed to be tight. It is evident, however, that since the gauge is connected beyond the outlet valves, this process only tests the outlet valves of the pump, and not the pistons or inlet valves. It is therefore wholly illusory as a test of the pump itself.

To test the real efficiency of a pump the following process has been used in our experiments from the outset (*see* Figure 4). The delivery-pipe attached to the pump was connected at its far end with a short piece of ordinary stout hose-pipe capable of being compressed readily by a large screw clamp or spanner. This hose-pipe was connected in turn with the inlet of an ordinary dry gas-meter of "30-lights" capacity. To test the pump, the number of revolutions which it required to deliver 10 or 5 cubic feet of air was counted, the clamp being usually at the first test freely open, at the second screwed up till the gauge showed a pressure of 100 feet of water, and at the third screwed up to a pressure of 200 feet. As a rule each cylinder was tested separated, use being made of the handle for connecting each cylinder separately. The percentage leakage or loss at each pressure could be calculated from the number of revolutions needed to deliver a given quantity of air. Thus with a single cylinder, if there was no leakage, 100 revolutions would suffice to deliver 10 cubic feet. If 150 revolutions were needed, the leakage would evidently be 33 per cent.; if 200, it would be 50 per cent.; and if 300, it would be 67 per cent.*

The first tests made with the pump used at sea, and which had caused so much distress to Instructor Watkins, showed a leakage of 49 per cent. at 100 feet pressure, and 79 per cent. at 200 feet, in the left cylinder, the leakage from the right cylinder being somewhat less. Thus with the left cylinder the diver would only receive at 100 feet about half the air-supply calculated from the strokes of the pump, and at 200 feet only a fifth. At 17½ fathoms, the depth at which Instructor Watkins tooks his sample, the air-supply needed by a diver would be 6·3 cubic feet per minute, according to the table set out above. With such a leakage he could only have received 1·5 cubic feet a minute from one cylinder, or 3 feet from the two cylinders, with the pump going at 30 revolutions per minute, about as fast as four men could drive it. At 200 feet he would only have received 1¼ cubic feet from two cylinders, instead of the 11·5 feet required according to the table. It was, in fact, quite evident that any attempt to do serious work in more than about 12 fathoms with a pump in this condition could only end in reducing the diver to a condition of intense distress.

A series of careful quantitative tests made at the Physiological Laboratory, Oxford, showed that although there was slight leakage at the inlet and outlet valves of the pumps, this was trifling in amount with the pump running at its usual speed. The great cause of leakage was failure of the leather cups of the pistons to act; and this failure could only be very partially and temporarily remedied by soaking the leathers in oil, and other similar means. In pumps which had been long in use the leakage was considerable, even with no adverse pressure; and in one old pump in use on a vessel in Portsmouth no air at all was delivered from one of the cylinders at 200 feet pressure, when the pump was working at an ordinary

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* For testing a pump under ordinary Service conditions a steel cylinder of known capacity could be used in place of a gas-meter; and experiments on this point are quoted in Appendix III.

speed; and only 7½ per cent. of the proper delivery when the pump was working at 40 revolutions per minute.

The following table shows the results obtained in the case of a number of pumps in use on vessels at Portsmouth, and tested under the supervision of Dr. Rees at ordinary rates of working:—

PERCENTAGE LEAKAGE of ordinary SERVICE DIVING PUMPS in use on SHIPS at the Time in PORTSMOUTH HARBOUR.

No. of Pump.	Cylinder.	0 Feet Pressure per Cent. of Leak.	100 Feet Pressure per Cent. of Leak.	200 Feet Pressure per Cent. of Leak.
3452 - - -	Left - - -	0	29	87
	Right - - -	0	38	58
3452 - - -	Left - - -	0	16	43
	Right - - -	0	26	36
3303 - - -	Right - - -	8	49	55
	Left - - -	12	35	72
1826 - - -	Left - - -	40	70	100
	Right - - -	23	31	46
1826 - - -	Left - - -	0	16	67
	Right - - -	12	28	36
2890 - - -	Left - - -	0	16	33
	Right - - -	12	25	83
1333 - - -	Left - - -	0	24	68
	Right - - -	25	37	72
2046 - - -	Left - - -	10	33	63
	Right - - -	12	37	66
2101 - - -	Left - - -	23	55	71
	Right - - -	20	30	59
1837 - - -	Left - - -	20	60	60
	Right - - -	10	12	22
	Mean - -	11·3	34·6	57·0

In view of the varying leakage existing from day to day in the available pumps, it was found necessary, in continuing the experiments at Spithead, to test each pump before or after use, at about the corresponding pressure and rate of revolution; and the air-supply, as given in the table of analyses, is based on these tests. The percentage of leakage can easily be calculated, if required, from the air-supply as compared with the revolutions per minute and number of cylinders used.

As it was evident, also, that one double pump could not furnish sufficient air for diving in deep water, arrangements were made for connecting together the deliveries from two or three double pumps. Experiments also showed that the greatly increased quantity of air thus delivered could still escape freely from the helmet with the outlet valve well opened, and that the pipes were of sufficient diameter to pass this air to the diver without causing any undue resistance. The resistance caused by pipes and valves to the escape of a given quantity of air (measured at atmospheric pressure) becomes, of course, less and less in proportion to the depth of the diver, since this resistance varies as the square of the velocity, and directly as the density. Thus with a diver at 100 feet, or 4 atmospheres of absolute pressure, the density will be increased to four times, and the velocity of flow reduced to a fourth. This resistance will therefore be $\frac{4}{16} = \frac{1}{4}$ of what it would be at surface with the same air-delivery.

The arrangement finally adopted for connecting the pumps was a four-way junction-piece provided with taps and connecting junctions, so that in case of necessity a pump could be easily connected or disconnected with the diver down, and a second diver could be sent down from one of the same pumps after disconnection.

In view of the liability to leakage with the present pattern of Service pump, particularly after use for some time, the Committee communicated with the makers, pointing out the necessity for more reliable pistons for deep diving. As the result of a number of experiments, Messrs. Siebe, Gorman and Co. furnished a set of pumps with greatly improved pistons, which, when tested in the workshops by the method described above, gave excellent results. Some of these pistons were fitted with leather cups, carefully fitted and furnished with steel springs to keep the leathers closely applied to the cylinders. The others were furnished with metal piston-rings (*see* Figure 19). These pumps were used in the experiments in very deep water at Loch Striven, where they were tested almost daily with the meter, and both patterns, with the exception of one cylinder fitted with piston rings, continued to give uniformly excellent results, the leakage or loss being only about 24 per cent. at a pressure of 200 feet of water, and 12 per cent. at 100 feet pressure. This amount of loss might perhaps be slightly improved upon, but it must be borne in mind that there are certain unavoidable causes of loss. In the first place, a small volume of highly compressed air must be left in the end of the piston at the close of each stroke, although the clearance is very small; and secondly, the piston and cylinder are heated more or less, so that the incoming air will be warmed and will take up some of the condensed moisture, expansion being thus caused, and consequent diminution in the mass of air delivered by the next stroke. The water-jacket round the piston can only partially prevent the warming.

The following table shows the results of tests made in the workshop, before the pumps were sent out, of a set made at the end of the Loch Striven experiments; about six weeks later, after all the pumps had been used for some time; and of a further set made during colder, weather on November 1:—

Number of Pump and Description of Pistons.	Cylinder tested.	Percentage of Loss at a Pressure of 200 Feet of Water.		
		July 20. Before Deep Diving Experiments.	September 5. After Deep Diving Experiments.	Nov. 1.
3588. Both pistons with metal piston rings -	Right	22	24	23
	Left	29		
3592. Both pistons with leathers - -	Right	18*a*	22½	26
	Left	17		
3593. Both pistons with leathers - -	Right	18½	23½	25
	Left	18	18	24
3604. Right cylinder with metal piston rings.	Right	26½ per cent.	35	43·5
Left cylinder with leathers - - -	Left	17 „	24	23·7

The workshop tests were made with cold water slowly circulating through the water-jackets of the pumps, while the tests made on the "Spanker" were without this precaution; and, owing to the pumps being placed on deck over the boilers, the water standing in the jackets was about 7° F. above the air-temperature when the tests were made. This difference might account for the slightly greater loss in the second set of tests.

In order to ascertain the effects of heating of the water in the jackets on the delivery of air, one of the pumps was kept running continuously at 30 revolutions per minute and 200 feet pressure (88 lbs.), the temperature of the water (after mixing) being taken at intervals, and the delivery of air measured. The rise of temperature was as follows:—

——	Temperature of Jacket.	Rise of Temperature.
	Degrees F.	Degrees F.
At starting - - - -	59	—
After 15 minutes - - -	72	13
„ 30 „ - - -	83	24
„ 47½ „ - - -	92	33

The delivery of the pumps could not be measured simultaneously with the temperature, but the latter could be calculated by interpolation. The results were as follows, including a supplementary observation with the jacket artificially heated:—

—	Temperature of Jacket.	Percentage of Loss in Air-Delivery.
	Degrees.	
At starting - - - - -	59	20·5
After running 17 minutes - - -	74	27·5
" " 36 " - -	86	30·0
After hot water poured into jacket -	154	39·0

These results show that it is better to keep the jacket cool by changing the water, but that the loss caused by heating of the water is not very serious within an hour. With water slowly circulating through the jacket, the same pump, as reported by Messrs. Siebe, Gorman & Co., showed an increase in loss of only 2 per cent. after half an hour's work, as compared with an increase of about 9 per cent. in the above tests with the water remaining unchanged.

A further question investigated at the same time was whether any formation of CO_2, or even carbonic oxide (CO), occurred in the pumps in consequence of the heating of the oil from the great air-compression at each stroke. Any appreciable formation of CO would be a serious matter, and a sample of the air delivered after the jacket had been artificially heated, so that the conditions might be at their worst, was carefully tested for this gas by the blood method. No trace could, however, be detected. As the presence of this gas in the air delivered by compressors has often been suspected, it may be mentioned that no trace of it could be found by Dr. Haldane in the air delivered by compressors on Cornish mines,* although the temperature of the cylinders rises far higher than in those of a diving pump. It is, of course, essential to have an oil of extremely low flash-point, to prevent any risk of firing; and for deep diving, water in the jackets is absolutely essential. Firing of a cylinder, with consequent production of CO_2 and CO, would be disastrous.

The results of the other analyses were as follows :—

Temperature of Jacket.	Increase in CO_2 Percentage.	Decrease in Oxygen Percentage.
Degrees F.		
84	0·00	—
87	0·00	0·00
150	—	0·10
142	0·00	0·12

From these results it appeared that there was no formation of CO_2 by oxidation, but that when the jacket was made very hot a slight absorption of oxygen occurred. This would be of no disadvantage to a diver.

Assuming that pumps giving only about 25 per cent. of loss at 200 feet pressure, and a proportionally smaller loss at lower pressures, are available, we may now proceed to calculate the rate of pumping, and the number of cylinders and of men needed in order to give the amount of air already specified as needed by a diver in doing moderately hard work at different depths. In the following table this is set out :—

Depth in		Cubic Feet of Air per Minute.	Number of Cylinders needed.	Revolutions of Pump per Minute.	Work in Compressing, in Foot-Pounds, per Minute.	Number of Men needed for each Spell of Work.
Fathoms.	Feet.					
0	0	1·5	1	15	—	—
2¾	16	2·2	1	22	1,927	2
5½	33	3·0	1	30	4,440	2
11	66	4·5	2	22	10,500	4
16½	99	6·0	2	33	17,600	6
22	132	7·5	4	21	25,600	8
27½	165	9·0	4	27	34,000	12
33	198	10·5	6	23	43,000	18
38½	231	12·0	6	25	53,000	18

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* Report to the Home Secretary on the Health of Cornish Miners, 1904, page 88.

A good diver can no doubt usually get on comfortably enough with the quantities of air specified in the table, and half as much will suffice for him if he is doing no work; but whenever he has to exert himself much, as when he has to contend with tide or mud, or has got foul, he will need more than the specified air supply, and provision ought at least to be made to let him have a third more when necessary. Not only the analyses of air from the helmet, but many other observations made in the course of the experiments, confirm this.

For instance, at 30 fathoms Mr. Catto accidentally got foul of the coils of a wire hawser which he was shackling on to a weight representing an anchor. The two pumps supplying him with air were meanwhile, owing to the men being tired, only going at 24 revolutions per minute, so that the air supply was about 8 cubic feet per minute, which was not much short of 9·7, the calculated quantity. Although he was comfortable enough with this air supply as long as all went well, he found it quite insufficient when he was exerting himself to get free, and was so much affected by the CO_2 that before he had freed himself, after a struggle of 20 minutes with the coils of the hawser in soft mud and pitch darkness, he had begun to feel that he was in danger of losing consciousness unless he stopped to rest, which, however, he was unwilling to do, as he had already much exceeded the limit of time calculated to be safe at this depth. Next day, at the same place, he shackled on the hawser in 4 minutes from the time of reaching the bottom, and 7 minutes from leaving the surface, feeling no discomfort, with about the same ventilation as before.

At 23⅓ fathoms Lieutenant Damant found that with the two pumps at 24 revolutions (about the specified quantity) the air supply was not sufficient to enable him to continue for more than 6 minute, a heavy exertion in hauling a rope. The CO_2 pressure in the helmet air had risen to 4·28 per cent.

To take another instance, Mr. Catto was greatly affected by CO_2 when struggling out of mud at a depth of 42 feet, the pump delivering at the time 2·55 cubic feet of air per minute, and the CO_2 pressure indicated by a sample from the helmet being 7·42 per cent. of an atmosphere. The 3·5 cubic feet calculated from the table would have still been insufficient, fully a third more than this being required.

In order to have some sort of measure of the powers of a diver doing work with varying supplies of air, the following arrangement was employed. A spar with a block and pulley attached to the end (Figure 18) was rigged up from the deck of the vessel. Over the pulley a rope was passed, with a 56-lb. weight attached at one end near surface, the other end being rove through a second pulley attached to a 2-cwt. sinker on the bottom, so that the diver could stand upon the sinker and haul on the rope. An observer on deck counted the number of times the diver could lift the 56-lb. weight, and the height of each lift, a toggle being attached to the rope above water to facilitate observations. In the experiments at 23⅓ fathoms two pulleys were employed above water, so as to prevent the 56-lb. weight from getting foul of the rope. Except where the contrary is stated, the diver continued to heave the rope until he was exhausted and had to stop.

The following table shows the results of a number of observations :—

Diver	Depth.		No. of Feet at each Lift of 5-lb. Weight.	No. of Times lifted.	Feet lifted × Times lifted.	Time occupied, in Minutes.	Revolutions of Pump per Minute.	No. of Cylinders.	Air-supply in Cubic Feet per Minute.	CO₂ per Cent. in Helmet Air.		CO₂-Pressure in per Cent. of an Atmosphere.	
	Fathoms.	Feet.								Before Work.	After Work.	Before Work.	After Work.
Mr. Catto - - -	3½	21	3	36	108	13½	30	1	(2·3)*	0·63	1·30	1·03	2·13
Instructor Watkins - -	3½	21	3	28	84	4½	30	1	(2·7)*	0·38	1·14	0·60	1·87
Mr. Catto - - -	11⅓	68	4	38	152	14	30	4	(8·0)*	0·23	0·45	0·70	1·37
,, - - -	12½	75	3¾	11	41	5	30	1	(2·0)*	0·92	1·60	3·01	5·24
Instructor Hatchard -	11⅔	70	6	6	36	5½	30	1	(2·0)*	0·84	1·47	2·62	4·59
,, ,, -	11⅓	68	4	40	160	27½	30	4	(8·0)*	0·24	0·42	0·73	1·29
Diver A - - -	10⅚	65	1	8	8	1½	30	1	(2·0)	—	—	—	—
,, B - - -	10⅚	65	4	5	20	3¾	30	1	—	—	—	—	—
,, C - - -	10⅚	65	6	6	36	—	30	1	—	—	—	—	—
,, D - - -	10⅚	65	4	8	32	—	30	1	—	—	—	—	—
,, E - -	10⅚	65	8	5	40	—	30	1	—	—	—	—	—
Mr. Catto - - -	23⅔	142	5	11	55	9½	30	4	9·8	0·30	0·70 0·71	1·59	3·71 3·76
Lieutenant Damant -	23⅙	139	3	23	69	8	24	4	9·1	0·18	0·73 0·81	0·94	3·80 4·22

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* Approximate estimates.

In connection with the last two experiments it should be explained that Mr. Catto took his first air-sample during work after four lifts, and his second after seven more. He was not exhausted at the end, and could have continued longer. Lieutenant Damant, who was working faster, took his first work sample after five lifts, and his second after 18 more, when he felt exhausted and out of breath, the CO_2 pressure in his helmet having reached 4·22 per cent. His air supply was also a fifth less than that of Mr. Catto.

Taking the results of these experiments as a whole, they confirm in the most striking manner the conclusion that the special distress from which divers suffer in deep water, and which destroys their working powers, is due simply and solely to increase of the CO_2 pressure in the helmet, and that whatever the depth may be up to 35 fathoms, this distress can be entirely eliminated by supplying the quantity of air theoretically calculated as necessary. With a plentiful air supply, as in the first three and the sixth experiment, the diver could do about as much hauling on the rope as he could do above water, the work of pulling a stiff and tarry rope round two or three pulleys, so as to lift the 56-lb. weight, being somewhat exhausting. With a moderate supply of air, as in the last two experiments, the working capacity was markedly reduced; and with a distinctly insufficient air supply, as in the other experiments, which were made under ordinary Service conditions, work was quickly brougnt to a standstill by accumulation of CO_2 in the helmet air.

Many other observations, which it would be superfluous to mention in detail, led to exactly the same conclusion, which may therefore be regarded as quite definitely established.

It has already been remarked that the work required to heave round the pumps to the necessary extent increases with the depth much more rapidly than the increase in pressure. The increase in work is shown in the table on page 25. As a matter of fact, 36 men, working very hard in alternate 5-minute spells of rest and work, were scarcely able to keep up the proper air supply to the diver at 35 fathoms; and 24 men working similarly failed to supply quite enough of air at 30 fathoms. We calculated that about 3,000 foot-pounds per minute of pumping work represented the maximum which a man without previous training could be expected to do. Three men were employed on each handle of the pump, but owing to there only being room for two men, the work was done at a disadvantage. Longer handles, adapted for three men a side, were afterwards supplied by the makers, and with these the men were able to heave round at the proper speed. They were, however, near the limit of their power. Owing to the pressure at which the divers were working having also reached the limit of the gauge, and other difficulties, it was evidently impracticable at the time to go much deeper than 35 fathoms, and so further test the possibilities of manual pumping.

Part II.

THE DANGERS OF DECOMPRESSION IN DEEP DIVING.

Since the early days of diving in deep water it has been a well-known fact that divers, on their return to the surface from deep water, may develop very serious symptoms, consisting sometimes of an attack of breathlessness and syncope, which may end in death within a few minutes or hours; sometimes of motor or sensory paralysis, usually of the lower limbs and bladder; and sometimes of nothing worse than attacks of pain in the limbs or elsewhere. The paralytic attacks are specially common among divers in deep water, the affection being popularly known as "divers' palsy." The greater the depth at which divers work, the more serious does the risk on decompression become. Even, however, when most alarming attacks of asphyxial symptoms, or paralysis, have occurred, complete recovery usually follows—often with surprising rapidity.

Men who work in compressed air in caissons, diving bells, tunnels, or "tubes" under construction in soft ground below water-level, in mine-shafts being sunk through watery strata, &c., are subject on coming out to similar symptoms—known as "caisson disease." Work of this kind is usually carried on at a much less high air-pressure than that to which divers commonly go, but the duration of the exposure is far longer—usually 4 to 8 hours per day. Among these workers in compressed air the commonest symptoms are attacks of pain, usually in the limbs, often very acute, and called "bends" and "screws" by the men; but cases of paralysis and asphyxial attacks also occur. These symptoms usually develop within a few minutes to an hour after decompression. With pressures exceeding about 20 lbs. to the square inch (about 45 feet of water) cases begin to occur, and at anything over 30 lbs. pressure they become very serious in their frequency, unless great precautions are taken. Among divers, on the other hand, decompression symptoms are seldom met with unless the diver has been at more than 40 lbs. pressure (15 fathoms); and the comparatively short exposure of the diver undoubtedly accounts for this difference.

The cause of these various forms of trouble was successfully elucidated about 30 years ago by the French physiologist, Paul Bert,[*] by experiments on animals. When a gas is brought into contact with a liquid, the latter takes up the gas in simple solution (apart from any chemical affinity) until a state of saturation is reached. The amount thus taken up depends upon the "co-efficient of solubility" of the gas in the liquid and the temperature of the liquid, and varies directly with the pressure of the gas, in accordance with what is known as Dalton's Law. The blood passing through the lungs is practically in contact with the air breathed, and therefore takes up, when a man or animal is in compressed air, an increased proportion of nitrogen and oxygen in simple solution, in accordance with Dalton's Law.

The increased proportion of oxygen so taken up only adds slightly to the total oxygen in arterial blood, since far more is normally taken up in loose chemical combination with the hæmoglobin; and in any case nearly all the *free* (*i.e.*, uncombined) oxygen of the blood disappears when the latter reaches the tissues. Carbonic acid is of course also present in the lung air to the extent of about 5·6 per cent. at ordinary pressure; but the compressed air makes no difference as regards the solution of CO_2 in the blood, since, as already explained in Part I., unless the air breathed is very foul, the pressure of the CO_2 in the lung air is kept constant by the breathing, whatever the total atmospheric pressure may be.

The increased proportion of nitrogen taken up by the blood in compressed air passes to the various semi-liquid tissues, which gradually also become saturated, since nitrogen, unlike oxygen, does not disappear by entering into chemical combination. The whole body thus gradually becomes saturated with nitrogen at the pressure (79 per cent. of the total atmospheric pressure) which this gas exerts in the compressed air. That the blood does

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[*] *La Pression Barométrique*, Paris, 1878.

actually become saturated with nitrogen in this way was shown by Paul Bert, whose results have been confirmed and extended by subsequent observers.*

If the excess of air-pressure is now rapidly removed, as occurs when a diver comes quickly to the surface, or a worker in a caisson passes rapidly through the air-lock, it is clear that the blood and tissues will for a time be in a condition of super-saturation for the diminished pressure. In consequence of this the nitrogen will tend to liberate itself within the body in the form of bubbles, just as CO_2 is liberated in bubbles when the cork of a bottle of soda water is removed. When a liquid is saturated by contact with a gas the pressure exerted by the gas in solution is the same as that of the gas in contact with it. The gas in solution will tend to liberate itself in the form of bubbles if its pressure in the liquid exceeds the total external pressure. Thus if the blood and tissues be saturated with air at 4 atmospheres pressure (*i.e.*, at 3 atmospheres above normal) the nitrogen in solution will *tend* to liberate itself in bubbles as soon as the external pressure falls below 79 per cent. of 4 atmospheres, *i.e.*, below 3·16 atmospheres.† It does not follow, however, that any actual, or at any rate any rapid, formation of bubbles will occur, particularly in the case of an albuminous liquid like blood. In practice there seems to be no danger in sudden decompression unless the absolute pressure is reduced to less than half what it was; and the lowest pressure by rapid decompression from which a fatal accident has occurred in a caisson worker, is, so far as we have been able to ascertain, 23 lbs. per square inch, or 2·6 atmospheres of absolute pressure, corresponding to 53 feet of sea-water. The occurrence of symptoms of any kind does not seem to be observed with pressures of less than 2·3 atmospheres, or 19 lbs. (43 feet of sea-water).

Paul Bert proved by numerous experiments on animals that sudden decompression from considerable pressures commonly causes death with symptoms of asphyxia, or else paralysis. The higher the pressure, and the longer, within certain limits, the exposure to it, the more absolute the certainty of death becomes. On examination of the bodies of the animals post mortem he found the veins in various parts of the body full of bubbles consisting almost entirely of nitrogen; and in the cases with symptoms of asphyxia the right side of the heart was full of froth, which had completely blocked the circulation.

The symptoms of paralysis were evidently due to partial or complete blocking of vessels supplying the spinal cord or brain; and in animals which had survived the paralytic attack for a few days, softening and the usual degenerative changes were found in the spinal cord at the places where the block had occurred.

Paul Bert's main conclusions have been confirmed and greatly extended by several subsequent observers. By a suitable arrangement Hill and Macleod‡ were able to see through a microscope the bubbles forming in the capillaries of a frog's web. After keeping the animal at a pressure of 20 atmospheres for 10 minutes, during which the circulation went on quite as usual, they suddenly lowered the pressure to normal, and observed that "for "about a minute after decompression the circulation continued unaltered, "then small dark bubbles were seen, first one, and then another, and then "numbers scurrying through the vessels and driving the corpuscles before "them. In a moment or two the vessels became entirely occupied with "columns of air-bubbles, and the circulation was at an end." By means of "rapid re-compression the gas was again driven into solution, and the "circulation became re-established, the animal being uninjured.

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* Pure air consists of 79·04 per cent. of nitrogen (including ·92 per cent. of argon), 20·93 per cent. of oxygen, and ·03 per cent. of CO_2. In the air of the lung alveoli the oxygen is diminished by about 6·5 per cent. and the CO_2 increased to 5·6 per cent. at normal atmospheric pressure; but in compressed air as the pressure rises the alveolar air differs less and less in composition from pure air. The whole body will take up nearly 1 per cent. of its volume of nitrogen for each atmosphere of pressure. Thus a man of 70 kilos (11 stone) may take up nearly 700 cc. of nitrogen for each atmosphere of air-pressure to which he is exposed. [This is an underestimate, as shown in the Supplement.]

† Or, say, 3·26 atmospheres, since allowance must be made for the small pressure of CO_2 and oxygen in the venous blood. This pressure (about 10 per cent. of one atmosphere) adds itself to the nitrogen pressure, and the nitrogen bubbles contain (at atmospheric pressure only) about 10 per cent. of CO_2 and oxygen.

‡ *Journal of Hygiene*, Vol. 3, page 436, 1903.

The results of post-mortem examinations of the bodies of men who have died after decompression have, when conducted in a competent manner, confirmed Paul Bert's experiments. Perhaps no case has been more completely investigated and recorded than the following, reported in the "Health of the Navy" for 1900, by Fleet-Surgeon A. M. McKinlay, who was assisted by Surgeons Forrester and Forest.

M.D., aet. 33, P.O., 1st class, was employed diving for a torpedo in 24½ fathoms of water at Lamlash on November 28th. He was a man of exceptionally good physique, not obese, and perfectly healthy. A warrant officer was in charge of the diving party, and owing to the great depth of water, took particular notice of the time. He states the man took 40 minutes to reach the bottom, that he remained there 40 minutes, and took 20 minutes to come up. This latter he did himself slowly and steadily without hurry, the men in the boat only taking in the slack of the rope. He climbed up the ladder on the boat's side himself, and on the face-plate of the helmet being removed, he said he felt alright, and then came into the boat with the ordinary assistance to be undressed. When the helmet was taken off, he answered a number of questions about his work, and gave a most detailed account of the same. He also joked with the other men, who all say they never saw him, or anyone else, come up in better condition. He felt perfectly well all the time he was in the water, suffered no inconvenience whatever, and only came up because it was so dark in the depth he was in that he could find nothing. He was cheerful and sensible, and had absolutely no symptoms whatever of anything wrong till some 8 or 9 minutes had elapsed from the time of his leaving the water. He then suddenly complained of pain in the stomach, and asked them to be quick and get off his dress, as he wished to get on board. In a second or two after he said, "Send for the doctor," and immediately slid down in the boat quite limp and unconscious. Fleet-Surgeon McKinlay saw him at once, and found him in a comatose state. His skin was cyanosed and his breathing was stertorous, laboured, and difficult. His lips were blowing and covered with froth. He was taken out of the dress and carried to the sick bay, but death took place before he got there, viz., about 15 minutes after reaching the surface, and 6–7 from the first symptoms of illness. He had no vomiting, convulsions, or spasm of muscles at any time.

A post mortem examination was made on the next forenoon, 23 hours after death, with the assistance of Surgeons Forrester and Forest.

Rigor mortis was well marked. Post mortem staining marked about neck and lower limbs. On incising the scalp, a quantity of very dark coloured, almost black, fluid blood flowed from the cut vessels, principally the temporals. On removing the calvarium, the veins over the whole surface of the brain were deeply engorged with the same dark fluid blood, and on removal of the brain a large quantity escaped from the vessels at the base. A careful examination was made of the pons, medulla, and upper inch of the cord. There was no evidence of any laceration or extravasation of blood. Numerous small blood vessels were marked in the cord, &c. by the black puncta produced by the exuding black blood, but up to this no air was seen. On making sections of the hemispheres, nothing abnormal was noticed until the lateral ventricles were opened up. These contained little or no fluid. The striking point was the presence of bubbles of air in large quantities in the veins of Galen and choroid plexus, these had a beaded appearance, and showed prominently against the dark background of the plexus. On examination of the veins of the surface of the brain, which by this time were emptied of their blood, they were found to be in a similar condition. On opening the thorax, the lungs were found absolutely healthy. They appeared to contain less blood than usual, and were not engorged. The pericardium contained very little fluid. The heart was normal in size, but the veins on its surface under the serous membrane were markedly beaded with air. On lifting it up, it felt like a bladder half full of water, and, on making pressure to raise it, was heard to gurgle loudly, and a quantity of black frothy blood flowed from the sinuses at the base of the skull. On opening the right ventricle air came out with a puff, and a small quantity of black frothy fluid blood was still found, but no trace whatever of any blood clot. The left side of the heart was empty. All the valves were perfectly healthy.

On opening the abdomen, the small vessels of the mesentery at the attachment to the gut were found to be filled with air. The liver was very dark coloured and engorged, and on section the cut surface exuded such a large quantity of froth that it gave the impression that portions of the liver might float in water, but on trial they sank immediately. The spleen was black and enlarged, of a globular shape, 3¼ inches in thickness. It was friable, and contained dark blood and air; the latter not to the same extent as the liver.

The cellular tissue in the subcutaneous fat of the abdomen and underneath the sternum also contained small bubbles of air.

The autopsy disclosed that all his organs were healthy and that the principal abnormal condition was the presence of air in large quantities in the right side of the heart and in the whole venous system. . . .

. . . On a previous afternoon a man, T.L., age 22, A.B., went down in almost the same depth, viz., 23 fathoms. He took 25 minutes to go down, was on the bottom for 22 minutes, and took 18 minutes to come up; being only 22 minutes on the bottom to the other's 40. He, likewise, suffered no inconvenience when down, and was quite well on reaching the surface, but, unlike the other man, he remained in good health.

Figure 11 is from a photograph showing the appearances presented by the veins of a goat killed by rapid decompression from 100 lbs. pressure (corresponding to 39 fathoms), in the steel chamber at the Lister Institute. The animal fell over unconscious shortly after the pressure was reduced to normal.

Figure 12, from a section prepared by Lieutenant Damant, and kindly photographed for us by Dr. Coventon, of Oxford, shows the appearances presented by the spinal cord of a goat after death by sudden decompression from a high pressure.

Unfortunately, the records of other fatal cases which have occurred in the Royal Navy have been so incomplete as to be of little service in connection with the present Report.

The following extract from a short account by Fleet-Surgeon P. W. Basset-Smith, R.N.,* gives a vivid account of the dangers to which pearl divers in deep water are exposed:—

"While on board H.M.S. 'Penguin,' employed in surveying a part of the north-west coast of Australia, which was then an important centre of the pearl-oyster fishery, cases of divers' paralysis came under my notice now and then. The luggers contain about six men, mostly Japanese, occasionally Europeans, and are accompanied by a schooner which acts as a store and hospital ship. All the work is done in diving dress in depths of from 10 to 25 fathoms, the period of submersion being often 4 or 5 hours. Cases of slight paralysis were common, coming on suddenly on removal of the dress, but generally recovering completely. The following is the worst case I saw:—

"'Japanese, aged about 30. Had been working in 32 fathoms (by all 'considered to be a dangerous depth) about three weeks ago; immediately 'on removal of the dress he became paralysed, and has been so ever since. 'His condition was one of great emaciation, free from pain, but very 'apathetic. Temperature 103°; pulse 120; tongue furred; complete 'paraplegia with loss of control of bladder and rectum, and loss of sensation 'to the level of the umbilicus. There was a large deep bedsore over the 'sacrum, extending from the tuber ischii on either side to the crest of the 'ilium above, with a thick, black, extremely offensive slough partially 'detached. It had eaten through skin, fascia, and gluteus maximus, and in 'places exposed the bone.' (He died three days later).

"The mate attending on him said that he had been as bad himself with bed-sores and paralysis for 8 months. He now walks with a limp, but muscular power is fair and tissues firm, kneejerks increased. He said that a very bad sign is a localised swelling of the abdomen, from which, if allowed to get under the ribs, death is certain, and that they apply any pressure to keep it down, even sit on it—probably a paralysis of intestinal muscles and collection of flatus. Those in charge told me that they tried to prevent men from going down over 20 fathoms, but as they are paid by results, it is very little use."

For further details, and for a discussion of other theories which have been unsuccessfully put forward to explain caisson disease, and which still sometimes re-appear in medical literature, we must refer to Paul Bert's book; to a large and most valuable treatise recently published by Heller, Mager, and

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* *Lancet*, I., 1892, page 309.

von Schrötter,* and to the papers of Dr. Leonard Hill, F.R.S., and his colleagues.† Reference may also be made to Dr. Snell's book, *Caisson Illness*, London, 1896, to Dr. Haldane's article on the subject at page 41 of the *Text-book of Pharmacology and Therapeutics*, edited by Dr. Hale White, 1901, and to *Der Sauerstoff in der Prophylaxe und Therapie der Luftdruckerkrankungen*, Berlin, 1906, by von Schrötter.

The dangers of decompression do not seem to have been the main actual cause which has prevented the prosecution of diving in very deep water. The great oppression, of which we have discussed the causes and prevention in Part I., has probably been the chief hindrance. How very great, nevertheless, the risks of rapid decompression are, is abundantly shown by the records of accidents to divers, as set out in the books and papers quoted.

There is much evidence to show that in different individuals the risk arising from decompression at a given rate, after exposure for the same time to the same pressure, varies very considerably. This has been observed particularly in the case of workers in caissons and subaqueous tunnels. In the case of the East River Tunnel at New York, for instance, new hands are subjected not only to medical examination, but also to a preliminary shorter exposure to compressed air, before being engaged; and those who experience any symptoms in the preliminary test are excluded. In the case also of divers variability in susceptibility would seem to exist, some men appearing to be immune from symptoms under conditions where other men are affected. In their experiments at the Lister Institute, Dr. Boycott and Lieutenant Damant made the same observations with respect to goats, some of the animals being relatively immune. (*See* Appendix I.)

For this reason, the fact that one diver has repeatedly escaped serious decompression symptoms, under certain conditions, does not prove that other men would be equally immune; and we think that a considerable margin of safety is desirable beyond what would seem to have proved safe in individual cases. As, moreover, susceptibility to decompression symptoms has been shown to increase after middle age is reached, it seems desirable that men beyond 45 should not undertake deep diving.

The problem before the Committee with respect to decompression was to devise such precautions that a diver not specially immune to decompression symptoms could both have time to do useful work at the bottom, and be able to return with safety to surface.

There are two methods of securing safety in decompression. One is to limit the time during which the diver is exposed to high pressure; and the other is to bring him up very slowly.

In very deep diving the first method is chiefly used—if only for the reason that the diver cannot stay below on account of the distress caused by the CO_2 pressure. In diving for pearls and sponges at great depths, it appears to be the practice for the diver to sink rapidly to the bottom, remain there for 2 or 3 minutes, and then come rapidly to the surface. When the destroyer "Chamois" sank in 32 fathoms off Patras, in the Mediterranean, in 1904, several Greek and Swedish divers descended repeatedly in order to examine the hull, so as to clear up the cause of the sudden disaster. They were able to get down for 3 or 4 minutes at a time, and to return as rapidly, without accident, although they did not succeed in their object. They were usually about 10 minutes under water. The depth (about 32 fathoms) is the greatest to which we have been able to find any record of divers penetrating safely. The other case in which this depth is reported to have been reached proved fatal to the diver, as already stated in the extract from Basset-Smith's paper. Another diver, who is reported to have reached 34 fathoms, perished on returning to the surface.

A remarkable case of immunity from symptoms, in spite of relatively rapid decompression, was that of the celebrated diver Alexander Lambert. Messrs. Siebe, Gorman & Co. (to whom we are indebted for information about Lambert and others of their divers) inform us that during the salving of 70,000*l.* worth of gold at a depth of 27 fathoms, he descended 33 times—usually twice, and

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* Heller, Mager, and von Schrötter, *Luftdruck Erkrankungen*, Vienna, 1900 (2 volumes).

† Hill and Macleod, "Caisson Disease and Divers' Palsy," *Journal of Hygiene*, 1903, page 401; also *Proc. Royal Society*, Vol. 70, page 455, 1903; *Journal of Physiology*, Vol. 29, page 388, 1903; Hill and Ham, *Journal of Physiology*, Vol. 33, page vi, 1905; Hill and Greenwood, *Proc. Royal Society*, B., Vol. 77, page 442, 1906.

sometimes thrice per day. He stayed 20 to 25 minutes below, took 2 to 3 minutes in descending, and only 4 to 5 in ascending. In his last descent he unfortunately stayed down for 45 minutes, and about half an hour after ascending he became completely paralysed in the lower part of his body. From this attack he never completely recovered. His immunity with only 4 or 5 minutes spent in decompression, in spite of a stay of 20–25 minutes on the bottom, was nevertheless very remarkable.

Another equally remarkable record is that of Érostarbe, employed by the same firm. He succeeded in salving a quantity of silver at the great depth of 29 to 30 fathoms. During this work he made about 70 dives without injury, his time below water from the surface and back being strictly limited to 20 minutes, and latterly to 15 minutes. He took 3 to 5 minutes to descend, and about 3 minutes to come up, so that he was on the bottom about 8 to 13 minutes. On one occasion he remained under water for 40 minutes, and about 15 minutes after returning he became very ill, suffering great pain. His condition seemed so serious that the Last Sacrament was administered to him. The skin of his legs, arms, and shoulder became black from extravasations of blood. He was quite well again a week later, and continued his work.

When the period of exposure to high pressure is limited to a short time, the blood and tissues have not time to become saturated with nitrogen at the high pressure, and the risk of bubbles being formed on decompression is thus obviated.

Experience in caissons proves that even after an hour the tissues are not completely saturated, since the risks on decompression are very much less than after two or more hours. Persons remaining under pressures up to 35 lbs. (13 fathoms of sea-water) for an hour are seldom affected seriously on decompression, provided this is not very rapid. As the pressure increases, however, the period of exposure has to be much reduced to secure safety by shortness of exposure only; and at 30 fathoms 10 minutes' exposure would certainly be dangerous with very rapid decompression, as in that time the blood and part of the tissues would have time to become sufficiently saturated to give rise to considerable risk.

The second method, which has been strongly recommended by Paul Bert, and all others who have worked experimentally at the subject, has been for long employed by divers doing serious work in very deep water, although they usually also confine their stay on the bottom to a short period, such as 10 to 20 minutes.

One of Messrs. Siebe, Gorman & Co.'s divers, A. Briggs, in salving gold coin at a depth of 27½ fathoms, made 12 dives, during each of which he spent about 12 minutes in the wreck, and occupied about 10 minutes in descending and 12 minutes in ascending. Another diver, Rayfield, went recently to 30 fathoms in Loch Long, taking 15 minutes to descend and 21 minutes to ascend. At the same place, Diver W. R. Walker went for about the same time to 28 fathoms, and took about 20 minutes to ascend, with stops of about 2½ minutes every 5 or 6 fathoms. He had previously worked two shifts a day for 3 months continuously in 21 fathoms of water in a well in London, spending half an hour on the bottom at work, and taking 20 to 25 minutes in ascending. Another diver, G. Maycock, during light work at 22½ fathoms in a well in London, spent 20 minutes on the bottom and came up in 7 minutes. In a subsequent piece of work at Datchet Waterworks, in 100 feet of water, he was seized with "pressure" in the legs and arms after working hard for 45 minutes at the bottom, and coming up in 5 minutes.

For caisson workers exposed for several hours to pressures exceeding about 22 lbs. per square inch slow decompression is essential. As to the necessary slowness, however, there is much divergence of opinion, with corresponding differences in practice. As a result of his experiments Paul Bert concluded that at least 12 minutes per atmosphere (14·7 lbs. or 33 feet or 10 meters of sea-water) should be allowed in decompression from high pressures. Heller, Mager, and von Schrötter recommend 20 minutes for each atmosphere, and Hill and Macleod make practically the same recommendation for pressures exceeding 30 lbs. (11 fathoms). In the recent experiments of Hill and Greenwood, the latter went in 55 minutes to a pressure of 92 lbs., equivalent to 206 feet of sea-water, and was then decompressed in 2¼ hours at a rate of about 20 minutes per atmosphere. In spite of this he had attacks of pain in both arms after decompression. In other experiments Hill and Greenwood went to 75 lbs. pressure, and were decompressed at about 20 minutes per atmosphere of pressure, or 1¾ hours in all. On several occasions they experienced localised pain after decompression, and found that these symptoms were absent when care was taken to move the joints and muscles during decompression, and massage the skin. They were lying down in the chamber during these experiments.

The engineering practice in connection with work in caissons and tunnels has nearly always hitherto been to decompress the men much more rapidly; and even when strict regulations have been laid down by the engineers for slower decompression the regulations have frequently been disobeyed by the men. To mention striking instances of rapid decompression, quoted by Paul Bert, the men were regularly decompressed in 10 seconds from the caissons used in building the bridge at Scorff, in France, the depth reached being 59 feet (25½ lbs. per square inch) in one caisson, and 40 feet in the other. There were only 2 deaths and 14 other serious cases, although the number of passages of men through the air-lock was 8,042. Decompression in 2½ minutes from a pressure rising to 36 lbs. (84 feet of water) would seem to have been the practice in building the bridge over the Seine at Argenteuil, and no deaths appear to have occurred. Dr. Foley, who reported on the effect produced on the men, recommended rapid decompression. The remarkable advice he gave to the men passing through the air-lock was "Si le brouillard épais et glacial qui ne manque pas de se produire vous "pénètre trop, hâtez-vous." A still more striking case was that of the bridge over the Mississippi at St. Louis, begun in 1869, the depth when rock was finally reached being 110 feet (48 lbs. per square inch). As the depth increased the length of shift was gradually reduced from 4 hours to one. Out of 352 men employed, 12 were killed and 18 seriously injured—a surprisingly small number, considering that the men are said to have been decompressed in 3 to 4 minutes. The doctor in charge, who was unaware of the real cause of caisson disease, was himself affected by paralysis after staying 2¾ hours at a pressure of 90 feet of water, but recovered completely. There were no more fatal cases when the length of shift was reduced to one hour, and none among the many visitors, including ladies, who were in the caisson for short periods, even at the greatest depth reached.

These facts will be no surprise to those who are acquainted with practical diving. Divers frequently come up in 3 or 4 minutes from depths of 15 fathoms or more without ill-effects, although accidents occasionally happen. The comparatively short time under high pressure is greatly in a diver's favour; and if this time be sufficiently reduced, a diver can safely ascend within one minute from even 25 fathoms or probably much more.

In recent times more care has been taken as regards decompression in the case of workers in caissons and tunnels, but although the risks have in this and other ways been greatly reduced they have not been obviated. The most extensive undertaking at present being carried out with the use of compressed air is the double tunnel under the East River at New York. About 120 men are employed in one three-hour shift daily at a pressure of 34 lbs. (corresponding to 76 feet, or 12⅔ fathoms of sea-water). Through the courtesy of Messrs. S. Pearson and Son, Ltd., Westminster, the contractors, we have been supplied with information as to the number of cases of both slight and serious affections among the men. These have been carefully recorded by Dr. F. S. Keays, medical director appointed by the firm. During the 4 months from April 1st to August 1st of this year the cases have been as follows:

"Mild cases" (temporary pains in the limbs, &c.) -	515
"Severe cases":	
Dizziness - - - - - -	27
Abdominal pain - - - - -	21
Pain and prostration - - - - -	7
Partial paralysis - - - - -	6
Complete paralysis (now nearly well) - - -	1
Deaths - - - - - - -	4

One of the deaths was in the case of a lock-tender, who, contrary to regulations, decompressed himself rapidly through the mud-lock. The time normally allowed for decompression was 15 minutes. All serious cases are treated, wherever possible, at once, and nearly always with marked success, in a medical air-lock, the use of which was first introduced by Mr. E. W. Moir, M.I.C.E., of Messrs. Pearson and Son, Ltd., many years ago, and is now general. The mortality (neglecting the mud-lock case) is at the rate of one death per 15,000 decompressions, a great improvement on the older statistics for work of this kind. Further efforts are, however, now being made by the contractors to eliminate the risk to life, since they have been disappointed in their expectation that the precautions already introduced would fulfil this end.

Before describing the precautions actually adopted in the deep diving experiments carried out for the Committee by Lieutenant Damant and Mr. Catto, it is necessary to discuss in more detail the processes occurring in the body during exposure to compressed air and during decompression. Absence of a careful consideration of these processes has, we think, led to many mistakes in the practice hitherto adopted.

There is every reason to believe, although experimental evidence on the subject is not yet complete, that the blood passing through the lungs becomes instantly saturated or desaturated to the exact extent of the pressure of the nitrogen in the air breathed. Whatever, therefore, the pressure of nitrogen in the air breathed may be at a given moment, the nitrogen pressure in the arterialised blood leaving the lungs will be exactly the same. During compression, as a diver goes down, the blood leaving his lungs will always be charged with dissolved nitrogen in proportion to the absolute pressure of the air he is breathing, *i.e.*, to the atmospheric pressure at surface (= about 14·7 pounds per square inch, or 33 feet of sea-water) plus the pressure of the water. The same will hold for decompression as he comes up, and since the arterial blood leaves the arteries within half a minute at most, and bubbles scarcely seem to form within this time, there will be no risk of bubbles actually forming in the arterial blood during decompression, except when it is almost instantaneous. With very rapid decompression, however, small bubbles which have passed through the capillaries of the lungs may easily increase in size in the arteries.

If the nitrogen in only the blood had to be taken into consideration, the problem of safe decompression would be easily solved. The weight of blood in healthy men, which has recently been measured by Haldane and Lorrain Smith,* averages 4·9 per cent. of the body-weight, so that a man of 70 kilos, or 11 stone, will have 3·2 litres or 5·6 pints of blood. The time which the blood requires to complete a round of the circulation in man is not definitely known, and certainly varies considerably for different parts of the body, according to the varying physiological requirements of different tissues or organs. We can, however, form a rough idea of the average time required. The average venous blood returning to the right side of the heart has been found in animals to have lost about 6 to 8 per cent. by volume of its oxygen, while the air breathed loses (in man) about 4 per cent. by volume of its oxygen. Assuming, therefore, that not much oxygen is normally used up in the lungs themselves, we may conclude that the volume of blood passing through the lungs is about half the volume of air breathed. The volume of air breathed per minute during rest by a normal average man is, however, about 7 litres per minute (measured dry at 0° C. and 760 mm.). Hence the blood circulating is about 3·5 litres per minute. Roughly speaking, therefore, a quantity of blood equivalent to the whole blood volume will, on an average, pass round the circulation once a minute during rest. If, therefore, only the blood had to be considered, as has often been assumed, we might conclude that the whole of it would be saturated, or nearly saturated, with nitrogen after exposure of a minute or two to a given pressure of nitrogen in the air, and that the danger of nitrogen bubbles forming in the blood would cease a minute or two after sudden decompression.

The actual conditions are, however, far more complex, since we have to consider not only the excess of nitrogen in the blood, but also the excess in the tissues. Just as in the lungs the nitrogen pressure of the blood becomes by diffusion equal to that of the air, so in the tissues of the body a similar

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* *Journal of Physiology*, Vol. 25, page 331, 1900. The accuracy of the method employed by Haldane and Lorrain Smith has recently been verified in animals by Douglas, *Journal of Physiology*, Vol. 33, page 493, 1905.

equalisation process takes place, by diffusion through the thin walls of the capillaries; and the venous blood leaving the capillary vessels of the tissues will consequently have about the same nitrogen pressure as the tissues themselves. Thus in the case of a man exposed to high air-pressure the nitrogen pressure of the venous blood will not become equal to that of the air until the tissues have also become saturated. Now the mass of the whole body is $\frac{100}{4 \cdot 9}$ = about 20 times the mass of the blood; and its capacity per unit weight of taking up nitrogen in solution is probably nearly as great as that of the blood. Hence it will take a very considerable time to saturate the tissues of the body with nitrogen in compressed air, or desaturate them on decompression. The process will also be a very lingering one, since the blood will at each round of the circulation yield less and less nitrogen to the tissues, or vice versâ, so that the point of complete saturation or desaturation will form an asymptotic limit.

Let us assume, for purposes of calculation, that the blood distributes itself evenly all over the body, and that the person is at rest, and is suddenly placed in compressed air. In the first round of the circulation (*i.e.*, in the first minute) the tissues (since they have 20 times the mass of the blood) and venous blood will become about $\frac{5}{100}$, or 5 per cent., saturated with the excess of nitrogen which would correspond to complete saturation. The second minute will add $\frac{5}{100} \times \frac{95}{100}$, or $4 \cdot 75$ per cent.; the third will add $\frac{5}{100} \times \frac{90 \cdot 25}{100} = 4 \cdot 5$ per cent.; the fourth will add $\frac{5}{100} \times \frac{85 \cdot 75}{100} = 4 \cdot 3$ per cent.; and the fifth $\frac{5}{100} \times \frac{81 \cdot 5}{100} = 4 \cdot 1$ per cent. Thus in 5 minutes the tissues will have become saturated to the extent of $5 \cdot 0 + 4 \cdot 75 + 4 \cdot 5 + 4 \cdot 3 + 4 \cdot 1 = 22 \cdot 65$ per cent. of the difference between saturation at atmospheric pressure and at the pressure of the compressed air. In the next 5 minutes the addition will evidently be $= 22 \cdot 65 \times \frac{100 - 22 \cdot 65}{100} = 17 \cdot 5$ per cent. of the same difference, and in the next, $22 \cdot 65 \times \frac{100 - 22 \cdot 65 - 17 \cdot 5}{100} = 13 \cdot 6$ per cent. Thus in a quarter of an hour the tissues will have reached $53 \cdot 7$ per cent. of the difference. Roughly speaking, we may say that in a quarter of an hour the process of saturation will have gone half way; in half an hour three-fourths of the way, in three-quarters of an hour $\frac{7}{8}$ths of the way, and in an hour $\frac{15}{16}$ths of the way. Thus if the assumption that the blood distributes itself evenly were correct we should expect to find that after an hour the tissues and venous blood of a man placed in compressed air at 32 lbs. pressure would be saturated to 30 lbs.

Actually, however, the rate of average saturation will not be so great. The blood is certainly not evenly distributed throughout the body. Some parts, such as the grey matter of the central nervous system, and the muscles and glands during activity, have a far greater blood supply than other parts, such as the connective tissues, fat, skin, joints, white nervous matter, &c. The parts plentifully supplied with blood will therefore saturate up rapidly, and cease to take more, while the parts scantily supplied will saturate slowly, so that in many parts of the body the tissues and venous blood will not be more than three-quarters saturated, or even half saturated, after an hour. On this point our knowledge is as yet very incomplete, but some ideas can be formed from practical experience in connection with work in compressed air. It seems perfectly clear from the experience of workers in caissons and tunnels that, other things being equal, the probability of bends, &c. occurring is very much less if the duration of exposure to compressed air is confined to one hour. As to longer periods of exposure, Mr. E. W. Moir, who has had very great experience on this subject, informs us that he is confident from his observations that a limitation of the exposure to even 3 hours distinctly diminishes the risk of "bends," as compared with 6 or 8 hours' exposure. The recent observations of Mr. G. W. M. Boycott in connection with the caisson work for the new High Level Bridge at Newcastle (*Proc. Inst. of*

Civil Engineers, Vol. CLXV., page 231, 1906) point in the same direction. We may therefore conclude that even after 3 hours of work in compressed air some parts of the body are not fully saturated with nitrogen, and that these parts are not more than half saturated after one hour's exposure.

Let us now consider the process of desaturation during and after decompression. If the pressure were lowered suddenly, and no bubbles were liberated, desaturation of the tissues and venous blood would occur at the same rate as saturation. If the blood were evenly distributed, about 22 per cent. of the excess of nitrogen would disappear in 5 minutes, and about 50 per cent. in 15 minutes. If the pressure had been 30 lbs., or 2 atmospheres, there would be no possibility of bubbles forming or increasing in size after 70 minutes, since the combined pressure of nitrogen, CO_2, and oxygen in the tissues and venous blood would not equal the atmospheric pressure. As, however, the blood, is not evenly distributed, it will be far longer before this point is reached in the case of some of the tissues; and practical experience agrees with this expectation, since the symptoms known as "bends" and "screws" (pains in the joints and muscles) may appear, or increase in intensity, several hours after decompression, if the period of exposure to compressed air has been considerable.

It is evident that if the air-pressure is lowered gradually and evenly, the nitrogen pressure in the tissues must lag further and further behind the fall in the pressure of the air, however slow the decompression may be. Let us assume that the blood and tissues are saturated at 40 lbs. pressure, that the air-pressure is lowered at the rate of 2 lbs. per minute from 40 lbs., and that the blood is evenly distributed throughout the body. At the end of 5 minutes the air-pressure will be 30 lbs., and during these 5 minutes the average pressure will have been 35 lbs. The nitrogen pressure in the tissues will now have fallen about 22·5 per cent., or say 20 per cent. of the difference between 35 and 40 lbs. It will therefore correspond to saturation at a pressure of 39 lbs. of air, or 9 lbs. above the actual pressure of the air. After the next 5 minutes the air-pressure will be 20 lbs., while the nitrogen pressure in the tissues will correspond to $39 - \frac{39-25}{5} = 36 \cdot 2$ lbs. of air, or 16·2 lbs. above the actual pressure of the air. After the next 5 minutes the excess in the tissues will be 21·9 lbs.; and when atmospheric pressure is reached it will be 26·5 lbs., certainly a dangerous excess. With the actual blood distribution in the living body this excess will of course be much greater in the case of some parts of the body, and much less in the case of others. For example, in the case of tissues which required an hour to become half saturated in the compressed air, and a correspondingly long time to reach full saturation, the excess would be 36 lbs.

We have now to consider the risks from formation of bubbles during decompression. Experience seems to show clearly that even with rapid decompression there is practically no risk of symptoms from bubbles being liberated unless the air-pressure exceeds about 20 lbs., and that even with 25 lbs., symptoms are not common, though with higher pressures the liability very rapidly increases, and becomes very marked when a pressure of 30 lbs. is exceeded. It therefore seems fairly safe to assume that practically no bubbles at all are liberated by the blood and tissues unless the pressure has exceeded 15 lbs., or one atmosphere above atmospheric pressure. Now the *volume* of gas capable of being liberated on decompression to any given pressure is the same if the *relative* diminution of pressure is the same. Thus the volume of gas, if any at all were liberated, would be the same on decompression from 2 atmospheres of absolute pressure (15 lbs. pressure by gauge) to one atmosphere (normal pressure), as it would be on decompression from 4 atmospheres absolute (45 lbs.) to 2 (15 lbs.), or from 8 atmospheres absolute (103 lbs. pressure, or 38½ fathoms of sea-water) to 4 (44 lbs., or 16½ fathoms). It therefore seemed very probable that there will be no appreciable liberation of bubbles with any of these pressure-diminutions, even when sudden. A number of experiments on animals, made by Dr. Boycott and Lieutenant Damant in the steel chamber at the Lister Institute, have, so far, borne out this hypothesis. Sudden drops of even 60 lbs. were in several cases observed to be tolerated with impunity if the absolute pressure was not more diminished than to a third, whereas drops of

45 lbs. with the absolute pressure diminished to a fourth caused very serious symptoms.

The danger of bubble-formation thus appears to depend upon the difference in *relative*, and not absolute pressure, between the air and the nitrogen dissolved in the tissues. We may therefore provisionally assume, pending the completion of the experiments at the Lister Institute, that this difference must be in the proportion of more than two to one before bubbles form appreciably; and that decompression can be safely proceeded with if the difference is not more than in the proportion of about two to one.

The practical deductions from these conclusions are of considerable importance, since in all probability safe decompression can be conducted with considerably less expenditure of time than if it is carried out by uniform diminution of the air-pressure, as has been hitherto usually recommended. It has already been shown above that the *absolute* difference between the air-pressure and the nitrogen pressure in the tissues necessarily goes on increasing during uniform decompression, and is greatest at the end of the decompression, so that uniform decompression is without the slightest doubt an unsuitable procedure. When, however, we also take into account that it is the *relative*, and not the absolute, difference in nitrogen pressure that matters, the unsuitability of uniform decompression becomes far more evident. In the case previously taken as an instance—uniform decompression in an air-lock during 20 minutes, of a man saturated at 40 lbs.—the relative pressures at the end of each successive 5 minutes of decompression, even on the extremely favourable assumption that the blood distributes itself evenly throughout the body, would be, assuming the atmospheric pressure to be the normal one of 14·7 lbs.: $\frac{39 \cdot 1 + 14 \cdot 7}{30 + 14 \cdot 7}$, $\frac{36 \cdot 2 + 14 \cdot 7}{20 + 14 \cdot 7}$, $\frac{31 \cdot 9 + 14 \cdot 7}{10 + 14 \cdot 7}$, $\frac{26 \cdot 5 + 14 \cdot 7}{14 \cdot 7}$, or 1·20, 1·47, 1·89, 2·80. The relative differences of pressure would thus be in the proportion of 20, 47, 89, and 180, or roughly 1, 2·3, 4·4, and 9·0. With uniform decompression the risk of bubble-formation, if any, is thus, as it were, concentrated in an acute form at the end of decompression.

Practical results fully bear out this theoretical deduction. Such a thing as the occurrence of symptoms during decompression is, we believe, almost unheard of, either among workers in caissons and tunnels or among divers. "On ne paie qu'en sortant," as the matter was put with characteristic French neatness by Pol and Watelle, who, 50 years ago, first gave a detailed medical account of the symptoms.

It seems evident that with uniform decompression a great part of the time spent in the process is time lost, for during the greater part of the time spent in uniform decompression the difference in pressure between the nitrogen in the tissues and that in the air is much less than it might safely be made; and as a consequence the nitrogen is given off from the lungs much more slowly than would be safely possible. If the absolute pressure were reduced without delay to about half, much time would apparently be saved without overstepping the limits of safely. For instance, at 41 lbs. pressure by gauge (92 feet, or 15¼ fathoms of sea-water, or 3·8 atmospheres absolute) the absolute pressure is about 56 lbs., and half of this is 28 lbs., or 13 lbs. by gauge, 30 feet of sea-water, or 1·9 atmospheres absolute pressure. The pressure could apparently be reduced at once in the air-lock to 13 lbs., or the diver be brought up to 30 feet, or 5 fathoms, without risk from bubble-formation, however long he had been exposed to the pressure. The rest of the decompression could be carried out slowly, and with gradually increasing slowness as atmospheric pressure is approached; the rate being so calculated that the difference in relative gas-pressure between the air and any part of the tissues should never exceed a safe limit, such, for instance, as two to one.

Let us consider what this safe rate would be, assuming that the whole body was saturated with nitrogen at 41 lbs. pressure, that the blood was evenly distributed in the body, and that the decompression was carried out by stages of ·3 atmosphere, corresponding to 10 feet for a diver, or 4½ lbs. by gauge in an air-lock. It would be safe to reduce the pressure by 0·3 atmosphere when the nitrogen pressure in the tissues did not exceed that corresponding to saturation with air at 1·6 × 2 = 3·2 atmospheres; and this point, calculating as has been done above, would be reached in about 8 minutes, so that the diver might then come up 10 feet, or the pressure in the air-lock be let down 4½ lbs. Before the next stage the nitrogen pressure in the tissues would require to fall to $1\cdot3 \times 2 = 2\cdot6$ atmospheres, which would occupy about 10 minutes; and before the next, or final, stage, the nitrogen pressure in the tissues would have to fall to $1 \times 2 = 2$ atmospheres, for which about 13 minutes would be needed. Thus 31 minutes in all would be needed. As, however, the blood is not evenly distributed, in consequence of which some parts of the body must take at least four times as long to desaturate as has just been assumed, the time calculated as desirable for decompression must be correspondingly extended, so that at least $4 \times 31 = 124$ minutes will be actually needed in order to prevent symptoms occurring, or about 100 minutes if we assume that it is safe to ascend to surface when the maximum nitrogen pressure in the tissues does not exceed about $2\cdot3$ atmospheres, or 19 lbs. by gauge. So far as they go, the experiments on goats have borne out this calculation, since they have clearly shown that a decompression rate based on the assumption that the blood distributes itself evenly in the body is unsafe. Practical experience in connection with caisson and tunnel work points clearly in the same direction. The calculation shows that even with stage-decompression about an hour and a quarter at least would be needed for the safe decompression of a man whose body was saturated at a pressure of 35 lbs. The numerous cases of caisson disease which occur when only 15 or 30 minutes are allowed for decompression after a shift of several hours' duration at this pressure are therefore just what might be expected. In the caisson work connected with the construction of new locks, &c., on the Danube Canal at Nüssdorf, a decompression rate of 1 lb. per minute was adopted for men working at 30 to 35 lbs. pressure. In spite of this and other precautions, there were many cases of caisson disease, including two deaths, as recorded by Heller, Mager, and von Schrötter, in the book already referred to.

A calculation similar to the above will show that it would take, at the best, about 3 hours to decompress safely a man whose body was saturated at a pressure of 30 fathoms, or 80 lbs. With uniform decompression the time needed would probably be much longer. Such long periods of decompression as an hour or more may be practicable in connection with work in caissons, tunnels, &c., but not in the case of diving under ordinary conditions. It is thus absolutely essential to limit the period of stay of a diver on the bottom if the depth exceeds about 10 or 11 fathoms. To give a diver at the same time a sufficient time to carry out serious work it is also, however, necessary to take proper precautions in decompression. Even with caisson workers at pressures exceeding about 30 lbs., it is desirable to combine limitation of the period of continuous exposure with precautions in decompression.

The slow desaturation rate in some parts of the body explains what is perhaps at first sight a puzzling phenomenon in connection with decompression symptoms. These symptoms sometimes develop, or increase in intensity (at least in the case of tunnel or caisson workers, who have been long exposed to pressure) several hours after decompression: at a time, that is to say, when the formation of fresh bubbles could not be expected to occur according to the foregoing calculations. In such cases it is probable that what has really occurred, is that bubbles formed on decompression, or soon afterwards, have gradually increased in size until they have produced symptoms. A bubble once formed in any part of the body—for instance, in or about a joint—will continue to increase in size so long as the gas-pressure in the surrounding tissue exceeds the atmospheric pressure. By extending the calculation given above it will, however, be found that the gas-pressure in some of the tissues may easily continue to exceed the atmospheric pressure for 3 or 4 hours after rapid decompression, so that during all this time symptoms may develop or else increase in intensity. Even when symptoms occur soon after decompression, it is probable that small bubbles formed almost at once have taken some time to increase in size to a dangerous extent, and that this fact goes far to explain the length of the interval between decompression and the appearance of symptoms.

A man at rest, and exposed to an excess of pressure of 30 fathoms of sea-water (80 lbs.) for 5 minutes would not, according to our previous calculations, have his tissues saturated with nitrogen to more, on an average, than 20 per cent. of this pressure, *i.e.*, to not more than 16 lbs. pressure—a perfectly safe limit. But a diver exerting himself, and exposed in all probability to a pressure of CO_2, which by itself would greatly increase his circulation, might easily have some parts of his body, and particularly the grey matter of the central nervous system, which is so richly supplied with blood, saturated to a much greater extent, so that very rapid decompression, as by blowing up, would be risky. With every minute of further exposure the risk of rapid decompression would increase; and this risk would be chiefly due to bubble-formation in parts richly supplied with blood, such as the central nervous system, and any muscles specially used. The "bends" and "screws," which are such common and characteristic symptoms among caisson and tunnel workers after decompression, and which are probably due chiefly to nitrogen liberated comparatively harmlessly in connective tissues and joints and nerve trunks, seem to be rare among divers in deep water, who are chiefly affected by paralysis, &c., due to bubbles in the central nervous system, or else by asphyxial symptoms due to massive liberation of bubbles into the venous system, with consequent blocking of the circulation. The slowly saturating connective tissues, &c., have not had time to become saturated to any considerable extent.

The longer the exposure to very high pressure, the greater, up to a certain limit, will be the time needed for decompression. It may, however, be safely assumed that parts of the body which become rapidly saturated with nitrogen at high pressure will desaturate themselves with corresponding rapidity during decompression; also, that if the exposure to high pressure is sufficiently curtailed the parts which saturate and desaturate slowly will not have time to become highly saturated during the exposure.

In deep diving certain practical points are evidently of much importance. In the first place, the diver should get down to the bottom as quickly as the pressure on the drums of his ears, or the pressure of his dress round him, will permit. While he is descending he is taking up nitrogen all the way; and, roughly speaking, he will absorb during his descent, if it is at a uniform rate, half as much nitrogen as he would absorb during an equal time on the bottom. Hence time spent in descending is all to the bad. The advice usually given to divers to descend slowly into deep water is very unsound (unless, indeed, the air-supply from the pumps is so bad that the diver does not know whether he can get down at all). The present Service Manual for Divers recommends, for instance, a rate of descent of 15 minutes for 12 fathoms. At this rate a diver would take 41 minutes to get down 35 fathoms; and before he touched bottom he would already be most dangerously saturated with nitrogen. A good diver is not troubled by his ears,* and if he has a plentiful air-supply from the moment of submersion his dress and helmet will never press upon him, owing to compression of the air within the helmet as he goes down. Lieutenant Damant and Mr. Catto were easily able to reach bottom at 35 fathoms in 2 minutes from starting down, though they would certainly have had to stop owing to pressure of the dress or panting, had their air-supply been inadequate.

Another equally important point is to get up out of the very high pressure as quickly as is safely possible. The reasons for concluding that a diver can come up quickly to half the absolute pressure with safety have already been stated. At 12 fathoms the absolute pressure is half that at 30 fathoms; and at 12 fathoms a diver is already out of any formidable pressure. Let us suppose that, instead of coming straight up within 3 or 4 minutes to 12 fathoms, a diver who has been down for a few minutes at 30 fathoms ascends at a uniform rate of 12 fathoms in 15 minutes, as has been recommended. It will thus take him 15 minutes to reach 18 fathoms. This is not merely a waste of time, but exposes him to additional risk, about equivalent to an extra 15 minutes at 24 fathoms or 12 minutes at 30 fathoms, during which the tissues in at any rate most parts of his body will be absorbing nitrogen. Thus, supposing he comes up and goes down at a uniform rate, taking about 40 minutes each way, and spending 10 minutes on the bottom, the total period of exposure will be about equivalent to

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* If he has catarrh, and consequent blocking of his Eustachian tubes, he should not attempt deep dives, or descend at all without the greatest caution. The ear-troubles are, of course, proportional to *relative*, and not absolute increase in pressure; hence they diminish for any given increase in depth as the diver goes down. The first thing a diver has to learn is to manage his Eustachian tubes, and avoid all risk of injury to his ears.

20 minutes at 30 fathoms for going down, 10 minutes actually spent at 30 fathoms, and say, 12 minutes at 30 fathoms in coming up—42 minutes in all. He will be fortunate if he escapes an attack of paralysis, or asphyxia, or "bends," on coming to the surface, which he will reach in 15 minutes from 12 fathoms, and 5 minutes from 4 fathoms, the rate of ascent at the end being most dangerously fast.

In the fatal accident recorded by Fleet-Surgeon McKinlay, and referred to above at page 31, the diver took 40 minutes to descend to 24½ fathoms. If he went down at a uniform rate, this was equivalent to an extra 20 minutes on the bottom, where he actually remained 40 minutes. He took 20 minutes to come up, and probably not more than 5 minutes for the last 6 fathoms—the stage where rapid decompression is so dangerous. The risk he was running was thus a very great one. The second man referred to in the report, and who escaped without a symptom, took 25 minutes to go down, stayed 22 minutes at 23 fathoms, and came up in 18 minutes. His exposure was only equivalent to 12½ + 22 = 34½ minutes at 23 fathoms, or to 32 minutes at 24½ fathoms, as compared with 60 minutes in the other case. His risk was therefore much less, though it was certainly greatly increased by his slow descent and probable too rapid ascent near surface.

In the case of a diver whose stay on the bottom in deep water has been very short, the reasons for hastening not merely the descent, but all the ascent except the last part, are specially cogent. His only tissues which will have become at all highly saturated will be those which saturate and desaturate rapidly; no part of his body will be fully saturated; and the parts which saturate very slowly will not have taken up sufficient nitrogen to be capable of causing any trouble at all on decompression. He can thus be brought safely at a rapid rate to less than half the absolute pressure; and even the remaining stages can be greatly hastened. Delay at any depth beyond 8 fathoms may only increase his risk; and delay in the first half of his ascent will certainly do so.

We may now describe the precautions adopted in connection with the Loch Striven experiments from H.M.S. "Spanker." These experiments had two main objects. The one already referred to in Part I. was to test the possibilities of working at depths up to 30 fathoms, with a supply of air sufficient to keep the CO_2-pressure in the helmet within reasonable limits. The other object was to test the practicability and adequacy of the precautions previously agreed upon provisionally by the Committee as being desirable for the prevention of dangers on decompression. These precautions had been carefully thought out beforehand; and were determined upon partly in view of the theoretical considerations already discussed, partly as a result of the experiments in the steel chamber at the Lister Institute, by Dr. Boycott and Lieutenant Damant, and the previous experiments of Paul Bert, Leonard Hill, and others; and partly from a careful study of the available data as to accidents on decompression in connection with diving and other work in compressed air. We aimed at erring well on the safe side if we erred at all; and we were under a pledge to your Lordships to allow no risk to be run by the officers engaged in the experiments, so far as care and foresight could provide against risk.

Practical experience in both diving and caisson work seems to show that, provided decompression is not too rapid, a man may remain for an hour at a pressure of 15 fathoms of water, or 39 lbs. to the square inch, without risk on returning to atmospheric pressure. At the end of this time parts of the body with an average blood-supply will, as shown above, probably be saturated to about $\frac{15}{16}$ths with nitrogen at the pressure of the nitrogen in the air, while the parts very sparsely supplied with blood, such as the connective tissues, &c., will not be more than about half saturated, *i.e.*, saturated to the not at all formidable pressure of 7½ fathoms, or 20 lbs. Calculating in the same way, and allowing for the difference in pressure, parts with an average blood-supply will probably be half-saturated after a stay of 15 minutes at a pressure of 30 fathoms, or 80 lbs., while parts very sparsely supplied with blood will only be saturated to a pressure of 5½ fathoms. Some parts, such as the central nervous system and muscles in a state of activity, will, on the other hand, be more highly saturated than parts with an average blood-supply. On the whole, however, decompression from 30 fathoms after 15 minutes exposure ought to be about as safe as decompression from 15 fathoms after an hour's exposure. The experiments on animals in the steel chamber were, so far as they went, in accordance with this inference, although unfortunately no satisfactory short experiments at high pressures could be made, on account of the length of time occupied in reaching high pressures. We therefore fixed upon 15 minutes, including an allowance of half the time (about 2 minutes) spent in going down, and three-fourths of the time spent in coming up to 15 fathoms, as being probably a quite safe limit of time at 30 fathoms. For intermediate depths between 15 and 30 fathoms corresponding limits of time were calculated, and are stated on the table on page 46.

As regards decompression, the possibility had to be allowed for that parts with a naturally active circulation, such as the central nervous system, or muscles where the circulation had been specially active owing to the work done by the divers on the bottom, might be nearly saturated with even a short exposure on the bottom. It was, therefore, arranged not to bring the divers to less than half the absolute pressure without a pause. As a further precaution the diver, during each stop on the way up, kept his arms and legs in constant movement, so as to increase the rate of circulation, and so facilitate desaturation. The stops and times spent at each stop are shown in the table. It will be seen that for a 35-fathom dive the first step was to come up 20 fathoms in about 4 minutes. This is a reduction of 54 lbs. in the pressure, which would have been a risky drop had it been to atmospheric pressure, and not to a pressure 40 lbs. above it. The further steps were graduated with a view to meeting the increasing risk from liberation of bubbles; but the last step, from 10 feet to surface, was certainly the one attended with most risk, if risk there was.

At the first stop the air-supply was diminished to that from one double pump, working at a moderate speed. Most of the men working the pumps could thus be released, and it was considered that a small excess of CO_2 in the helmet air would stimulate the diver's circulation, and thus help him to get rid of his extra nitrogen. For a similar reason, an excess of CO_2 while the diver is on the bottom probably adds to his risks by increasing the rate at which he takes up nitrogen[*]; and this is a further reason in favour of a plentiful air-supply at great depths. An excess of CO_2 certainly adds also to his risk by hindering his work, and thus prolonging his stay on the bottom.

As a preliminary precaution, before the Loch Striven experiments both divers subjected themselves in the steel chamber at the Lister Institute to the pressures which they intended to go to under water, remaining at each pressure for the time agreed on, and decompressing themselves also in the manner agreed on. These tests were very severe, since it took about 45 minutes for the compressor to raise the pressure to 80 lbs. (30 fathoms pressure), in consequence of which the periods of exposure in the chamber at the highest pressures were virtually much longer than the times agreed on.[†] At the end of each decompression the subjects remained closed in the chamber for half an hour as a precaution, with the compressor running, so that at any moment recompression could be at once begun. This precaution was certainly necessary, as the risks were very considerable with so long a virtual exposure. No symptoms were, however, observed. Higher pressures than 80 lbs. were not tried in the steel chamber, since it was not originally intended to dive beyond 30 fathoms (80 lbs.).

A further precaution was taken in case symptoms should arise after the diver left the water. A small steel chamber specially built at Portsmouth Dockyard was carried on the deck of the "Spanker." This chamber, which is shown in Figure 12, is large enough to take two persons easily, and is provided with a door wide enough to take a diver with his dress on. It was connected with the compressed air reservoirs (used in firing torpedoes) by

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[*] Mr. E. W. Moir has drawn attention to the effect of adequate ventilation in diminishing the tendency to caisson disease; and this can be well understood in cases where the pressure of CO_2 had been allowed to get too high. Paul Bert quotes a case where the average CO_2 percentage in a caisson was found to be 2·36—a figure so high as to be almost incredible, however.

[†] With similar exposures to about 75 lbs. pressure, and similar decompressions, a considerable proportion of the goats had symptoms of "bends"; and one animal unexpectedly developed severe respiratory symptoms and died, as it could not be re-compressed at the time.

Depth		Pressure.		Virtual Time of Exposure to Specified Pressure.	Actual Time on Bottom.	Stoppage in Minutes during Ascent.								Total Time of Ascent in Minutes.
In Feet.	In Fathoms.	Lbs. per Sq. In.	Atmospheres, absolute.			At 80 Feet.	At 70 Feet.	At 60 Feet.	At 50 Feet.	At 40 Feet.	At 30 Feet.	At 20 Feet.	At 10 Feet.	
90	15	40	3·7	1 hr.	1 hr.	—	—	—	—	—	5*	5	10	22
108	18	48	4·3	40 mins.	40 mins.	—	—	—	—	5	5	5	10	27
120	20	53½	4·6	30 „	30 „	—	—	—	—	5	5	5	10	28
132	22	59	5·0	26 „	24 „	—	—	—	5	5	5	5	10	33
144	24	64	5·4	23 „	21 „	—	—	—	5	5	5	10	10	38
156	26	69½	5·7	20 „	17 „	—	—	5	5	5	5	10	10	43
168	28	75	6·1	17 „	14 „	—	5	—	5	5	5	10	10	43
180	30	80	6·45	15 „	12 „	—	5	—	5	5	5	10	10	44
210	35	93½	7·4	11 „	7 „	5	—	5	—	5	5	10	10	44

The diver to descend as fast as his ears or the pressure on his dress will permit; and to ascend at the rate of about 5 fathoms per minute. Time of each stoppage, except the first, to be counted from end of previous stoppage. Movements of the legs and arms to be continued during each stoppage.

* This stoppage was omitted in the experiments.

copper tubing, so that a diver could, if necessary, be re-compressed in it up to a pressure of 45 lbs. or more in 2 or 3 minutes. A bag of oxygen was also kept in readiness for the diver to breathe until he could be re-compressed. Fortunately, however, all the experiments went as we hoped and anticipated, neither diver having any symptom from beginning to end, although even the slightest symptoms were carefully watched for after each dive.

Before each dive the pump, and all the air-pipes and connections up to the point of attachment to the helmet, were carefully tested at a pressure considerably above that to which the diver was going.

It will readily be understood that if a burst occurred in the air-pipe, or a junction gave way, the diver would be instantly killed if the non-return valve in the air-inlet of the helmet failed to act. If, on the other hand, it acted satisfactorily, the burst pipe could be replaced, the diver being meanwhile brought up to a moderate depth as a measure of precaution, and if necessary, brought on by stages to surface. The air-supply in the helmet and dress, if he did not waste it, would probably last for 15 minutes or more during his ascent, as the effect of the increase in the CO_2 percentage in the air of the helmet would be counteracted by the decrease in pressure.

In order to test the non-return inlet valve of the helmet the piece of metal pipe containing it was unscrewed, connected in reverse direction with the pump, and immersed in a pail of water, so that the leakage could be measured by collecting the escaping air in a pint measure. When tested to a pressure of 100 feet of water it leaked to the trifling amount of one pint in 21 seconds, or ·06 cubic feet per minute of air measured at atmospheric pressure; and at 200 feet pressure the leakage was only ·07 cubic feet. Another inlet-valve was connected with a compressed air reservoir with a view to testing it to destruction. It was, however, almost uninjured at a pressure of 1,750 lbs., since when tested afterwards with air at 200 feet pressure it only leaked at ·12 cubic feet per minute.

Catsaras (quoted by Heller, Mager, and von Schrötter, page 259) records a case in which the air-pipe burst while a Greek diver was at a depth of 17 fathoms. Although the diver was at once brought up, he barely escaped with his life. When he reached the surface he was bleeding from the nose and scarcely conscious; and his face, eyelids, &c., were swollen to an enormous size. The valve on his helmet must evidently have been very leaky.

We have never heard of a burst in an air-pipe occurring in the Royal Navy, but it has happened on at least one occasion that an air-pipe became detached from the pump owing to a sudden and very violent wrench. No ill-effects followed, however, as the non-return valve acted satisfactorily. In case of a similar accident with the diver at 200 feet, a leakage of, say, ·1 cubic foot per minute of air measured at atmospheric pressure would be of no importance, as his helmet and dress would probably contain about 10 cubic feet of air measured at the same pressure. He would have plenty of time to be hauled up at a fairly safe rate, or to ascend the shot rope.

The diver was always connected by telephone with the deck of the "Spanker." This was a convenience in many ways, particularly when samples were being taken, or work experiments carried out, and when one of the divers got foul. During his ascent the diver was stopped at each stage by signalling on the breast-rope in the ordinary way. The gauge was watched during the ascent; and when the depth indicated by it was within about 10 or 20 feet of the proper stopping place the pumps were stopped, and the gauge tapped until it reached the proper indication, whereupon the diver was stopped by signal. There was never the slightest difficulty in stopping him at the right point within a foot or two. It was necessary to stop the pumps, as owing to the resistance in the pipes the depth shown by the gauge was several feet beyond the actual depth. The gauges had been specially tested, and were correctly graduated for fresh water. Thus, with the diver sitting on the bottom, at an actual depth of just over 35 fathoms, or 210 feet, as carefully measured on the shot-rope with a standard measure, the gauges showed a depth of 216 feet with the pumps stopped, and 220 feet with them going. A pressure of 216 feet of fresh water corresponds almost exactly to 210 feet of sea-water.

Appendix II. contains a short journal of the experiments at Loch Striven; and an account of the preliminary experiments on the divers at the Lister Institute will be found in Appendix I. The only incident which needs special mention was the mischance by which one of the divers got foul of a wire hawser in the mud and darkness on the bottom at 30 fathoms. As he was kept 29 minutes before he could get free, and as, owing to his exertions and the rather inadequate air-supply, his tissues were probably highly saturated with nitrogen, it was decided to give him double the usual time in coming up, the stops being all about double the usual time, and the ascent taking an hour and a half. It was a tedious experience for the diver, but better than risking the occurrence of "bends" or even more serious symptoms, and the experiments on animals at the Lister Institute had shown that decompression by stages in the usual time after so long an exposure would probably not have been safe. Each diver made only one dive per day. Owing to time necessarily occupied in sounding for the required depths, shifting the vessel's position, testing the pumps with the meter, analysing samples, and in other ways, more than two dives per day would have been difficult, particularly as Drs. Haldane and Rees had to sleep on shore at some distance. But it was also important to give sufficient time for any decompression symptoms to develop, bearing in mind that these symptoms occasionally appear several hours after decompression. It would also have certainly required some extra precautions as regards time on the bottom or decompression, if a dive had been repeated by the same diver within less than about 2 hours. Pearl and sponge divers who go down repeatedly for very short periods at a time, often develop symptoms after two or three dives. At the beginning of each successive dive their tissues are more and more saturated with nitrogen, and the additional saturation in the last dive may prove disastrous.

As no discomfort or other trouble was experienced at 30 fathoms, it was decided to dive to about the maximum limit which the pressure gauges on the pumps would show, and a depth of just over 35 fathoms (93½ lbs. pressure) was reached in the deepest dives, the time on the bottom being, however, cut down to 6 minutes to give an extra large margin of safety. It is perhaps instructive to compare these two dives with the experiment in which Dr. Greenwood exposed himself to a pressure very nearly as great in a steel chamber. On reaching 92 lbs. in 54 minutes, he was slowly and uniformly decompressed at a rate of about 22 minutes per atmosphere, this process taking 2 hours 17 minutes. After coming out he had an attack of "bends" in both arms. The divers, on the other hand, went down in 2 minutes, and came up in 44 minutes. With so short an exposure they could probably have come up without any serious risk of symptoms in 20 minutes. In consequence of the slow compression and the very slow and uniform decompression, which kept him for a very long time under extremely high pressure, Dr. Greenwood, who was fully an hour at an average pressure of 77 lbs., or 29 fathoms, must have been far more highly saturated with nitrogen than the divers, and yet at the most critical stage in the last atmosphere his rate of decompression was faster than that of the divers, who took 20 minutes after reaching the last 9 lbs. of pressure, while he took only 13 minutes.

The results of the various dives during the Loch Striven expedition, and of the corresponding experiments made upon themselves in the steel chamber by the divers, constitute a fairly solid body of evidence that, with the precautions set out in the accompanying table, diving to 30 fathoms is safe, at any rate, for a practised diver in perfectly good health.* Had any symptoms, however slight, been noticed, we should have felt much more doubtful in drawing such a conclusion.† It is very probable that a more rapid ascent, or else a longer

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* The system at present adopted in the Service of medically examining all divers before they descend, affords an important protection against accidents in diving. A man who is from any cause not in perfect health must undoubtedly be much more liable to be seriously affected by the formation of bubbles in his blood.

† The experiments on animals in the steel chamber at the Lister Institute have shown that with graduated decompression "bends" are far more likely to occur than any other symptom. Paralytic symptoms have not been observed. Any signs of "bends" were therefore most carefully watched for in the divers, since their occurrence would indicate the approach towards a danger limit.

stay on the bottom, is possible without running appreciable risk; and much will be gained if this turns out to be the case. The contemplated further experiments on animals and men in the steel chamber at the Lister Institute will afford valuable guidance in this respect, and bring out clearly the effect of each factor influencing the risks. The actually adopted limits of time on the bottom are, however, sufficient to enable a diver to do much valuable work, particularly if he is freed from all the usual discomforts and hindrances arising from an excessive pressure of CO_2 in the helmet air. The time allowed for coming up is doubtless a disadvantage; but the great waste of time hitherto usual in going down was avoided, so that a dive to a depth beyond 20 fathoms could be completed in less time than is at present taken if the recommendations of the Service "Manual for Divers" be adopted. A dive to 30 fathoms, with 12 minutes on the bottom, was completed within an hour. When the further experiments at the Lister Institute are completed we propose to issue a supplement containing a detailed table showing at a glance the precautions which we recommend during the ascent of divers from various depths and with various times on the bottom. Such a table might with advantage be affixed to the case of each diving pump. (This supplement is published at the end of the Report.)

The Loch Striven experiments were conducted from the deck of a torpedo-gunboat, about 8 feet above water-level. The diver had thus to climb some 8 or 10 feet of ladder before even his 40-lb. breast and back weights were removed, the total load being 155 lbs. This climb was a very exhausting process, and possibly the great strain accompanying it might tend to launch suddenly into the general circulation bubbles of nitrogen which had formed. To get on board a larger vessel would be still more difficult. A diving ladder provided with some means of hauling up a man standing upon it would be an improvement when diving is carried out from a vessel's deck.

If any of the very various symptoms which may arise after decompression have occurred, the question of treatment at once arises. For mere attacks of pain in the limbs, without any more threatening symptoms, such as shortness of breath or motor or sensory paralysis, palliative treatment will usually suffice, such as local friction, hot or otherwise counter-irritant applications, or the hypodermic injection of a small dose of morphia. For the radical and effective treatment of decompression symptoms by far the most effective plan is, however, re-compression. This plan was tentatively recommended even by Pol and Watelle, the earliest medical writers on caisson disease, and strongly urged by Paul Bert, as a result of his experiments. It seems now to be pretty well known among workers in compressed air in tunnels that their pains and troubles will disappear if they go back into the compressed air. We are informed, for example, that during the construction in compressed air of a tunnel under the Clyde the men were in the habit of going back, and even sleeping, in the tunnel, if they felt any discomfort after coming out from their day's work. In extensive engineering work in compressed air a "medical air-lock" is now usually provided for re-compression. This plan, combined with the precaution of keeping the men close by for some time after coming out from their work, was introduced by Mr. E. W. Moir, one of the firm of S. Pearson and Son, Ltd., who has had charge of various large subaqueous tunnelling undertaking carried out by them. It was first used, and with the most striking success, in connection with the first Hudson River Tunnel; and its employment has certainly saved much suffering, disablement, and loss of life.

It is evident that re-compression, if applied before any permanent damage has been done to the affected tissues by the cutting off of their blood-supply, or in other ways, must be very effective; and experience with men, as well as with animals, fully bears this out. In the first place the bubbles are at once diminished in volume proportionally to the increase in absolute pressure.* This causes instant relief of pain, and of any asphyxial symptoms. In the second place the bubbles begin at once to re-dissolve, if the air-pressure is high enough to make the nitrogen pressure in the bubbles exceed that in the

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* For instance, they will be diminished to a third if the pressure is raised to 3 atmospheres absolute (*i.e.*, 29·4 lbs., or 11 fathoms of water).

tissues. To enable this re-solution to complete itself, or go sufficiently far for practical purposes, some time must be allowed, after which decompression may be slowly and cautiously carried out. Even the paralytic symptoms disappear very quickly, as a rule, on re-compression, except in extreme cases, but any part of the central nervous system which has been (by blocking of the circulation) deprived of oxygen may take some time to recover; and if it has been for long deprived of oxygen it will not recover at all, although other parts may gradually take on its functions, so that the patient ultimately recovers more or less completely. The following case, reported by Dr. Gould, September 17, 1906, and communicated to us by Messrs. Pearson and Son, illustrates well the curative action of re-compression in the case of a workman in one of the East River Tunnels, who had worked 3 hours in compressed air at about 34 lbs.

A.R., aged 23. Symptoms came on about 8 p.m., while walking home. Began with numbness of both legs. Walked back two blocks, when legs were completely paralysed. Brought back to medical lock in ambulance. Complete motor paralysis in both legs, and very slight sensation. Knee-jerks present; no clonus; no pain or nausea; pulse good. Put in medical lock at 8.45 p.m., and pressure raised to 31 lbs. by 9.0. Could move legs slightly at 20 lbs.; walked feebly at 25 lbs.; walked perfectly well and sensation normal at 30 lbs. Came out at 9.42. Normal after decompression.

Sir Weetman Pearson, M.P., chief partner in the firm, was himself on one occasion attacked by paralysis of the legs shortly after coming out of the Hudson River Tunnel. The symptoms promptly disappeared on re-compression, although they partially returned the same evening after his return home, when he was at a long distance from the air-lock; and he did not completely recover for some days.

When no radical treatment is adopted the bubbles will ultimately disappear of themselves. This is due to the fact that the nitrogen pressure in the bubbles (about 90 per cent. of one atmosphere)* is higher than in the blood (about 79 per cent. of one atmosphere, corresponding to the nitrogen pressure in the air breathed). Thus nitrogen will slowly diffuse out of the bubbles, and they will ultimately disappear. The nitrogen bubbles in the blood itself may also, perhaps, leak out bodily through the lungs. At any rate it takes very little pressure to make air pass from the lung alveoli into the blood. The lungs are, in fact, astoundingly leaky to air; and unless air leaks out bodily from the blood into the lungs, it is very difficult to understand how small the effects sometimes are of slowly injecting enormous quantities of air into an animal's veins.

In view of the great additional safety and sense of security afforded by a re-compression chamber, it was thought advisable to provide one for use in case of any unforeseen accident in connection with the Loch Striven experiments; and this chamber is likely to prove of much service in future. It can not only be used for treatment in connection with any extensive deep diving operations, but also for experimental purposes, and for testing the ears of men undergoing diving instruction, and teaching them how to open their Eustachian tubes. For the latter purpose the chamber is invaluable; and after a lesson inside it two of the officers of the "Spanker," and a boy of 13 who was on board, had no difficulty in descending to the bottom in 6 fathoms of water, though none of them had ever dived before.

Re-compression chambers are not available in connection with ordinary diving work; but there remains the possibility of sending a diver down again should any serious symptoms threaten, should he be accidentally "blown up" to surface, or should he from any other cause have come up, or been hauled up, more quickly than is safe. There is an interval of some minutes at least before symptoms develop in consequence of rapid decompression; and if, for instance, a man has been blown up, there is plenty of time to haul him in, ease his valve, and send him down again. Even if

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* The average pressure of CO_2 in the tissues is probably about 7 per cent. of one atmosphere, and of oxygen about 3 per cent. Hence the bubbles, if at atmospheric pressure, will contain about 90 per cent. of nitrogen, 7 per cent. of CO_2, and 3 per cent. of oxygen. It is possible, however, that owing to blockage of the circulation or other causes the CO_2 pressure may rise greatly, in which case the bubbles may contain less than 79 per cent. of nitrogen, and will not dissolve, so that they perhaps remain for days.

very serious symptoms have already developed, and he is helpless, it is far safer to open his valve, give him plenty of air, and drop him down slowly and steadily on the life-line till he recovers, or the bottom is reached. He will probably have recovered by the time he is down a few fathoms, and another diver can be sent after him shortly. If he has no symptoms he can go down himself in the ordinary way till a safe depth is reached, as shown in the table which we have drawn up.

In any doubtful case, where symptoms seem possible, though not probable, the diver, on coming to surface, might remain in the water or on the diving ladder for 10 minutes before coming on board and having his helmet unscrewed. He could thus very easily again descend if he began to feel any symptoms. On coming on board he ought not to undress for another 20 minutes.

Another form of treatment which may be of value is the inhalation of oxygen. Benefit is to be expected in two ways from oxygen inhalation. In the first place, when pure oxygen is inhaled there is a very distinct increase in the amount of oxygen carried by the blood to the tissues. Part of this extra oxygen is combined with the hæmoglobin of the blood (which does not become fully saturated when ordinary air is breathed), and part is in simple solution, in accordance with Dalton's Law. This extra oxygen is of special value, since the whole of it is very readily available for physiological requirements; and in cases where the symptoms are due to deficiency in the supply of oxygen brought by the blood, the effects of breathing oxygen are very marked. Since, therefore, the most serious decompression symptoms are due to deficiency of oxygen from local or general blocking of the circulation, these symptoms are benefited by oxygen inhalation.

Oxygen also facilitates the disappearance of nitrogen bubbles, since it enormously increases the difference in nitrogen pressure between the nitrogen bubbles and the arterial blood, increasing this difference from 10 per cent. to 90 per cent. of an atmosphere. It was this consideration chiefly which led Paul Bert to propose oxygen inhalation as a method of treatment alternative to re-compression; and his experiments with oxygen gave favourable results.

On the "Spanker" the arrangement for inhaling oxygen was as follows:—An ordinary close-fitting face-piece without valves was connected by a piece of ½-inch rubber tubing and a wide tap with a bag containing about a cubic foot of oxygen. The bag was also provided with an outlet tap and an extra tap for running in more oxygen from a steel cylinder. The diver could thus, if necessary, be at once given pure oxygen to breathe.* With this plan the CO_2 of the air expired accumulates in the bag, which ought therefore to be partly emptied and then filled up again from the cylinder every few minutes. The CO_2 is, however, an advantage in so far as it stimulates the respiration and circulation, and thus facilitates the discharge of nitrogen.

There seems to be no reason why some means of giving oxygen should not be provided for in connection with ordinary diving. The oxygen could be conveniently generated from "oxylithe" and water, or else carried in steel cylinders.

It has been proposed in cases of impending asphyxia from air in the blood, to puncture the right side of the heart, and suck out the excess of air which has accumulated there, an ordinary fine trocar, cannula, and aspirating bottle being used for the purpose. This is a desperate remedy, but, to judge from experiments on animals, would sometimes save life.

A source of trouble and danger to divers in deep water is their liability to the accident known as "blowing up." If a diver gets his dress too much inflated he is of course lifted upwards. Once he has left the bottom the air in his dress expands more and more as the pressure diminishes, and he shoots upwards with increasing velocity. At or near the surface he may strike violently against a ship's or boat's bottom, and thus damage himself or his dress. When he reaches the surface from any considerable depth his dress is distended; he cannot move his arms; and he floats helplessly with his valve below water until he is hauled in. (*See* Figure 13.) The dress does not burst, as air can escape from his cuffs. Even if he could do so, it would be most

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* It would of course be dangerous to administer oxygen in a re-compression chamber with the pressure at anything over 30 lbs. The method sometimes adopted of giving oxygen by allowing it to come out in a fine jet near the mouth of the patient is both useless and ridiculous.

unsafe for him to let the air out and so sink down again. He could not check his descent, and might be squeezed to death if the pressure in the helmet became temporarily less by a very few feet of water than on his body. If he has been in deep water for any considerable time he also runs the gauntlet of decompression symptoms occurring; but if he is hauled in promptly, and goes down the shotted rope again without delay after the excess of air has been let out through one of his cuffs, or by holding his head up and opening his valve, there is probably not much risk, and he can be brought up again in the usual way by stages.

Any diver can of course blow himself up voluntarily, and it may be convenient to him to do so if he is in shallow water. So far as decompression symptoms are concerned, there can be little or no risk in blowing up from depths up to 7 fathoms. Accidental blowing up is only apt to occur when the diver is crawling on the bottom with his head down. When he puts his head down the escape of air from his valve is of course checked, and air accumulates in the back of his dress. If he allows too much to accumulate in this way without raising his head the air may get into the legs of his trousers, and he may then be capsized with his head down and be helplessly carried upwards. If he is wearing the "crinoline" the tendency to blowing up is naturally much increased, and we must distinctly condemn this antiquated and clumsy contrivance, although it perhaps gives a little relief when there is too much CO_2 in the helmet air. It seems to have been originally introduced with the idea of taking off some of the great pressure of the water at great depths. This pressure is in itself of not the slightest importance, and if it were the crinoline would be absolutely useless as a protection.

A number of experiments have been made by Lieutenant Damant and Mr. Catto to try whether it would not be preferable to have the main weights round the waist, instead of on the corselet. By this plan the risk of accidental blowing up is got rid of, but the weights tend to shift unless they are firmly fixed on, in which case it is difficult to get sufficient air into the dress to enable the diver to ascend the shotted rope without much effort. Finally the plan was adopted of lacing up the thighs and legs by means of the arrangement shown in Figures 1 and 2. By this means air is prevented from capsizing the diver by distending the trousers of the dress, and if too much air gets into the dress while he has his head down the helmet is carried up automatically, and the excess of air escapes by the valve. The tendency to accidental blowing up is thus got rid of, and the diver always comes upright, even if he has been placed upside down. Figure 14 shows the diving dress distended with air, with and without lacing up of the legs. Figure 15 shows a diver who has purposely blown himself up in the modified dress. It will be noticed that he is in the upright position. He would automatically assume this position before leaving the bottom.

In view of the great risk attending blowing up in very deep water, it seems desirable to discard altogether the "crinoline," and to adopt the plan of lacing up the legs, as just described. Failing this, the legs of the dress should be wound round with cord to prevent their distention with air, the knees being, however, left perfectly free.

Part III.

THE POSSIBILITIES OF VERY DEEP DIVING.

In Parts I. and II. we have dealt with the main difficulties met with in diving with the ordinary Service appliances up to depths of about 30 fathoms. It may be useful, however, to consider the possibilities of practically useful work at greater depths, and of extending the time on the bottom at depths exceeding 20 fathoms.

One difficulty not hitherto referred to arises from the fact that at depths exceeding about 25 fathoms the pressure of oxygen in the air breathed by the diver begins to be capable of producing serious effects. Among Paul Bert's other discoveries was the fact that oxygen at high pressure acts as a poison. He found that at an absolute pressure exceeding about 3 atmospheres of oxygen (corresponding to about 15 atmospheres of air-pressure, since air contains about a fifth of its volume of oxygen) animals go into convulsions and soon die, even a short exposure being often fatal. With an exposure of several hours a pressure of even 2 atmospheres of oxygen, or 10 atmospheres of air, was found to be dangerous.

Lorrain Smith[*] has shown recently that oxygen at high pressure acts on the lungs, producing pneumonia (inflammation of the lungs). He found that fatal pneumonia may be produced after 4 days' exposure to an oxygen pressure of as little as 75 per cent. of an atmosphere (corresponding to air at about 3½ atmospheres of absolute pressure, or at a depth of 14 fathoms). At a pressure of about 1¼ atmospheres of oxygen (6 atmospheres of air, or 28 fathoms of water) death from pneumonia was produced in about 48 hours. At about 1·8 atmospheres of oxygen pressure (8½ atmospheres of air, or 250 feet of water) marked symptoms usually occurred in about 12 hours, and death in 20 hours, though in one case the animal died in 7 hours. At about 2·8 atmospheres of oxygen (13½ atmospheres of air, or 70 fathoms of water) marked symptoms were observed in about 3 hours, and death in 9 hours.

To judge from these experiments, and a subsequent series by Hill and Macleod,[†] it would seem probable that in all probability a man supplied with air in the usual way might dive to about 400 feet, or say 70 fathoms, for a short time without much risk of ill-effects from the oxygen pressure, and that an exposure of less than 2 or 3 hours at 300 feet would not be dangerous. Further experiments on this subject are, however, evidently required.[‡]

To breathe pure oxygen for long at pressures much exceeding 2 atmospheres absolute, or 15 lbs. by gauge (33 feet of sea-water) is evidently risky, and at a pressure of 3 atmospheres, or 30 lbs. by gauge, is decidedly dangerous. It has been proposed to supply divers with pure oxygen, in order to avoid the risks arising on decompression from bubbles of nitrogen. Evidently, however, pure oxygen cannot be safely supplied for any considerable time at depths exceeding about 6 or 7 fathoms.

As has been already pointed out, the troubles arising from pressure of CO_2 in the helmet air can be overcome by increasing the air supply, pumps driven by power being, if necessary, substituted for hand pumps. There are, however, methods by which the amount of air required might be diminished.

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[*] *Journal of Physiology*, Vol. 24, page 19, 1899.

[†] *Journal of Hygiene*, 1903, page 401.

[‡] Since the above was written Dr. Boycott and Lieutenant Damant have tried on goats the effects of three hours' exposure to an oxygen pressure corresponding to 57 fathoms of water. Out of seven animals one died of pneumonia in the chamber, and most of the others seemed somewhat affected, though they rapidly recovered when the pressure was reduced. At an oxygen pressure corresponding to about 40 fathoms of water, Dr. Haldane and Lieutenant Damant could not detect in themselves any symptoms, either objective or subjective, during short exposures.

On the Continent a diving dress provided with an air-reservoir on the Rouquayrol and Denayrouze principle is much used. The diver carries on his back a steel air-reservoir, into which the air is delivered from the air-pipe. He breathes air from the reservoir through a reducing valve, drawing at each breath only the quantity of air required, and expiring through an outlet valve. By this plan the diver obtains tolerably pure air,[*] and only uses as much as he actually requires. The air-reservoir pattern has never come into use in England, however; and it appears to have certain definite disadvantages. In the first place, it is more complicated in construction and still more so in use, and liable to get out of order. It has also the disadvantage that the air-reservoir is apt to get foul of ropes, &c. under water, and to be otherwise in the diver's way. Another serious defect is that the attendant on the surface cannot see by the gauge the diver's depth, since the gauge indicates the pressure in the air-reservoir, and not the pressure in the diver's helmet. The work of pumping is also much increased, since the pressure in the reservoir is considerably greater than in the diver's helmet. Finally the diver cannot readily control his buoyancy, and if he stoops down so that the reservoir is above him, he has to breathe against pressure. There are, therefore, very substantial objections to the air-reservoir. On the other hand, there will be no risk with the air reservoir of the diver blowing up when he puts his head down, since no air will escape into his dress. There will also be less risk from falling, since if the diver falls air will escape freely from the reservoir through the breathing tube into the helmet, and the pressure in the latter will thus be prevented from becoming temporarily less than in the surrounding water.[†] On the whole, however, the advantages of an air-reservoir seem to be greatly outweighed by its disadvantages.

Another plan by which the air-supply might be greatly reduced would be to use an arrangement by which the CO_2 in the helmet air was absorbed. With such an arrangement an air-supply of one cubic foot per minute, *measured at atmospheric pressure*, would amply suffice at all depths, even during hard work, so that at 30 fathoms, for instance, only about a tenth as much air would be necessary. Various risks and complications would, however, be introduced by this plan, and for this reason we have not experimented with it.

In the Fleuss apparatus the air-pipe is dispensed with altogether, the diver obtaining oxygen from a steel cylinder and the CO_2 being absorbed by caustic soda. In comparatively shallow water this apparatus could be used with safety, provided sufficient precautions were taken to prevent any deficiency of oxygen from occurring. In deep water, however, oxygen poisoning would certainly occur, so that it is only in exceptional circumstances that the Fleuss apparatus would be specially useful—for instance, in cases where it is necessary to dispense with an air-pipe, and the depth is not great. We have, however, already reported on our experiments with this apparatus.

The most serious difficulty in connection with deep diving is undoubtedly that due to the dangers of decompression. In Part II. of this Report the means available for obviating these dangers under ordinary conditions of diving work have been fully discussed. Various further measures might, however, be adopted in cases where much work has to be done at one particular place in deep water, as, for instance, in salvage operations or work in connection with foundations.

Dr. Leonard Hill has proposed the plan of lowering to the bottom a steel chamber, into which a diver could get on the completion of his work, and close the door. The chamber could then be hauled to the surface, the pressure inside being lowered very gradually by allowing the air to leak out at a perfectly safe rate. In this way the danger of decompression could be completely obviated.

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[*] The pipe leading from the diver's mouth to the expiratory valve is charged with very foul air at the end of each expiration, and this air has to be taken in at the next inspiration, along with the fresh air from the reservoir, so that he always breathes vitiated air.

[†] This advantage is almost entirely neutralised if, as is customary, the air-reservoir is kept at only about 5 lbs. excess of pressure. The reserve of air in the reservoir is then quite trifling in amount—insufficient for a single good breath at depths of over 5 fathoms. In fact the whole arrangement becomes ridiculous.

This plan might, we think, be considerably simplified and shortened by adopting the principle of stage decompression proposed in Part II. The pressure in the chamber could probably be reduced very greatly within a few minutes, so that even if it were hauled rapidly to the surface it would not require to withstand an excess of internal pressure of more than one or two atmospheres.

Several advantages would be gained by the use of a submerged decompression chamber in this way. In the first place, the diver would be spared the long and tedious ascent through the water. During the ascent he is exposed to the risk of his hands becoming numbed from cold, so that he cannot hold on to the shotted rope. If, as is often the case, the tide is formidable, the risk of being carried away from the shotted rope is, of course, considerable, and a diver thus carried away will probably come to surface at once, and so be in danger of the consequences of sudden decompression. A second advantage of the submerged decompression chamber would be that in the event of any symptoms occurring the diver could be re-compressed at once. A third advantage would be that if his air pipe was attached to the chamber he would be saved the very formidable drag caused by the tide acting on an air pipe coming from surface, and he could thus work as easily at great depths as he could near surface, with a tide running.

Another plan available for prolonged work in deep water would be to use a diving vessel provided with a caisson about 3 feet in diameter passing by a well through the bottom to a point some 30 or 40 feet below the surface of the water. This caisson would be open below and would end above, inside the diving vessel, in an air-tight chamber, provided with an air lock for passing in or out, or two air locks, one of which could be used for recompression if necessary. The shotted rope would be attached to the open end of the caisson. The diver could go down to his work in the ordinary way from the ship's side, but on coming up could enter the caisson at its open end, and be brought up to the chamber at the upper end. He would thus be saved the long waits in the water during the later and longer stages of stage-decompression, and he could be decompressed at leisure, in the air lock, after a wait sufficiently long to make the process safe. With this arrangement if the excess of pressure in the caisson was one atmosphere (33 feet of water), and if sufficient time were taken before coming out from the caisson, it would be possible for a diver to work at double the absolute pressure without increasing the risk from decompression. For instance, at 30 fathoms, the absolute pressure is double that at 12½ fathoms; hence the diver could return as safely to the caisson from 30 fathoms as he could to surface from 12½ fathoms. A vessel fitted out with a movable caisson (used as a diving bell) was recently supplied to the Admiralty for use at Gibraltar. An illustration of this vessel is given in Messrs. Siebe, Gorman & Co.'s catalogue.

In order to diminish the time required for safe decompression it has been proposed to administer oxygen to divers. When pure oxygen is breathed the whole of the nitrogen gas dissolved in the blood and tissues of the body is gradually got rid of by diffusion through the lungs, so that bubbles of nitrogen cannot form on decompression. Since any excess of oxygen is rapidly consumed by the living tissues, bubbles of oxygen do not tend to form on decompression unless the pressure has been extremely high; or if they do form they are rapidly re-absorbed. If, therefore, the excess of nitrogen can be displaced from the body before decompression, it is possible to decompress rapidly without danger.

It has already been pointed out that it would be risky to administer oxygen to a diver at depths much exceeding 33 feet (2 atmospheres of absolute pressure). Hence the proposal to supply pure oxygen to divers just before their ascent from great depths must be dismissed as impracticable. Time could, however, be saved in decompression if the administration of oxygen were only begun at 30 or 40 feet. In stage-decompression as described in Part II., the object is to keep the gas-pressure in the venous blood and tissues about double, but not more than double, that of the air. By giving a diver oxygen to breathe after he has reached 30 or 40 feet from surface during stage-decompression the rate of loss of nitrogen by diffusion through the lungs will be about doubled. In other words, the venous blood will lose about twice as much nitrogen during its passage through the lungs. In consequence of this the time required for safe decompression will be reduced to about half in the last three or four stages.

Oxygen from a steel cylinder or oxylith generator could be quite conveniently given from a bag during decompression in a decompression chamber or air-lock. There would also be no difficulty in supplying it to a diver under water from a steel cylinder provided with a suitable reducing valve and tap, connected with the air-pipe. We believe that in cases where men are required to work under heavy pressure for any considerable time its employment would be very useful.

With the disappearance of the respiratory troubles which were dealt with in Part I. of this Report, it becomes doubly important to keep the question of safety in decompression always clearly in view. The further experiments which it is proposed to carry out at the Lister Institute will, we trust, throw considerable new light on this question, and go far towards defining the limits of what can safely be attempted at different depths.

Additional experiments are also needed with regard to the best means of avoiding the risks arising from a diver becoming badly fouled, and the difficulties caused by tide; also as to the supply of air by more effective means than hand-pumping.

SUPPLEMENT.

PRECAUTIONS RECOMMENDED IN ASCENDING FROM DIFFERENT DEPTHS AND AFTER DIFFERENT PERIODS OF STAY ON THE BOTTOM.

As shown in Appendix I., the experiments carried out at the Lister Institute on goats during 1906 and 1907, have furnished very clear evidence of the general correctness of the principles set forth on pages 39–44 of this Report, and of the marked superiority of the new method of bringing a diver up by graduated stages. They have at the same time furnished quantitative data from which the precautions needed in decompression after various periods of stay on the bottom, at various depths, may be deduced. These data were only very partially available at the time when the series of experimental dives from H.M.S. "Spanker" were undertaken; and it now appears that the precautions taken in the deeper of these dives were somewhat in excess. On the other hand, the rate of decompression in some of the experiments made on Lieutenant Damant and Mr. Catto in the steel chamber of the Lister Institute was a good deal more rapid than we should now consider safe for a diver after exposures of the same virtual durations and to the same pressures.

The Tables at the end of this supplement show in detail the precautions which we recommend. It will be seen at once that in order to carry out these precautions efficiently, it is necessary that the pressure-gauges on the diving pumps should indicate the depth of the diver correctly, and particularly at lesser depths. For this reason we wish to draw special attention to our recommendation as to the testing of these gauges. The following remarks will serve to explain the principles on which the Tables have been constructed.

(1) *Limits of safety in rapid Decompression.*

The experiments on goats have clearly shown that up to the limits of pressure investigated it is safe to decompress rapidly to half the absolute pressure or a little more, however long has been the exposure to the higher pressure. Thus a sudden drop from an absolute pressure of 90 lbs. to 39 lbs. produced not the slightest symptom, the fall in pressure being 51 lbs., and the ratio of the higher to the lower pressure being 2·3 to 1. On the other hand, a sudden drop from 66 lbs. absolute pressure to 15 lbs. (atmospheric pressure) produced disastrous effects on the same animals, the ratio of the two pressures being now 4·4 to 1, although the fall in pressure (51 lbs.) was exactly the same in amount as before. The goat experiments have also shown that slight symptoms first begin to appear with sudden decompression, when the ratio of the two pressures exceeds about 2·3 to 1, and the exposure to the higher pressure has been a long one. Human experience, so far as it goes, points in the same direction. Rapid drops from high absolute pressure to half or a little less produced no ill effects on Lieutenant Damant or Mr. Catto; and similar rapid drops to atmospheric pressure from twice atmospheric pressure or a little more are well known to produce no bad effects in divers or caisson workers. A case which may be quoted is that of the men employed in rock-drill work at the bottom of Gibraltar harbour in the diving bell attached to a small vessel already referred to at page 55. The men work four at a time in four-hour shifts (a very long exposure) at a depth of about 35 to 40 feet, and take 1½ to 2 minutes to come out through the air-lock. Mr. Catto, who is at present in charge of the vessel, has made careful enquiries as to whether any of the numerous men who have been employed during the last five years have ever shown any symptoms due to the decompression. He found that no such symptoms were known to have occurred at any time. Several of the men have been employed since 1902.

In view of this clear evidence we have assumed in calculating the table of precautions in ascending, that however long the stay on the bottom, it is safe for a diver to ascend rapidly until the absolute pressure is reduced to at least half; also that so far as risks of caisson disease is concerned, there is no need for any delay in ascending from depths of less than 7 fathoms or 18½ pounds of excess pressure.

(2) *Time required for complete saturation of the body with atmospheric nitrogen.*

The experiments on goats show that the symptoms produced by rapid decompression increase in frequency and gravity with the duration of exposure to high pressure up to two hours; longer exposures cause little or no increase in symptoms, so that maximum saturation is, practically speaking, reached in two hours. In man the rate of respiratory exchange and circulation of blood per unit of body weight is nearly half that of goats. Hence we may conclude that in man maximum saturation is practically reached in about 4 hours, or perhaps a little more; and this conclusion seems to accord fairly well with the human experience referred to at page 39. On the same page there is a calculation, according to which parts of the human body with an average circulation would be almost completely saturated in an hour.[*] This conclusion was somewhat difficult to reconcile with actual experience; and further investigation disclosed a very material source of error in the calculation. It was noticed by Dr. Boycott and Lieutenant Damant that in the bodies of goats which had been killed by too rapid decompression the fat was often remarkably full of gas-bubbles. No other tissue in the body showed the same phenomenon; and this led to the suspicion that the solubility of gases in fat or oil might be high. This suspicion was confirmed by some data published in connection with a quite different investigation by Dr. H. M. Vernon, Fellow of Magdalen College, Oxford. Dr. Vernon then kindly undertook a series of exact experiments with animal fats at the body temperature. These experiments[†] disclosed the very remarkable fact that nitrogen is about six times as soluble in fat as in an equal weight of blood at the body temperature. As the human body usually contains about 15 or 20 per cent. of fat, its capacity for holding nitrogen in solution must be nearly twice as great as was assumed on page 45. In other words the time required for saturation must be nearly twice as long. With this amendment the calculation accords much better with practical experience. It also follows that a fat man will take longer to saturate with nitrogen in compressed air, and to desaturate during decompression. He will, therefore, probably be less subject to caisson disease after short exposures to pressure, but more subject after long exposures, other conditions being equal.

Time required for safe Decompression.

As already explained, decompression can be carried out without risk of any symptom whatever, if during the process the partial pressure of nitrogen in any part of the body is never more than twice that of the atmosphere. In order to fulfil this condition without wasting time unnecessarily, it is necessary to know to what extent different parts of the body have become saturated with nitrogen during the exposure to pressure, and how rapidly they give off the excess of nitrogen during decompression. The general principles on which this may be calculated have been explained on pages 38–43. The later experiments on goats (Appendix I.) have furnished experimental data which enable these principles to be applied in detail, and at the same time demonstrate their general correctness. An actual example will best illustrate the mode of applying them. Let us suppose that a diver has to go to a depth of 28 fathoms (corresponding to an excess pressure of 75 lbs. per square inch, or 5·1 atmospheres), and that it is decided to allow him to remain only so long that he can come up safely within about half an hour. We may also assume that he can reach 28 fathoms in about 2 minutes.

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[*] Von Schrötter ("*Der Sauerstoff in der Prophylaxe und Therapie der Luftdruckerkrankungen,*" Berlin, 1906, p. 42) concluded that saturation must be practically complete in as little as 15–20 minutes.

[†] Communicated to the Royal Society, May 30th, 1907.

The logarithmic curve (Figure 20) represents graphically the average rate at which any portion of his body with an average circulation of blood, and an average proportion of fat, during rest, will probably become saturated with nitrogen if he is suddenly exposed to any given excess pressure. The curve is drawn according to the almost self-evident assumptions explained at page 39. Some parts will, however, saturate much more rapidly, and others more slowly. By simply altering the scale of time on the curve it is possible to take all these parts into consideration. For instance, a part which becomes half saturated in 5 minutes will be seven-eighths saturated in 15 minutes, while a part which becomes half saturated in an hour will only be about one-sixth saturated in 15 minutes.

Figure 21 shows graphically the calculated increase in saturation of different parts of the body of a diver who has gone to 28 fathoms in two minutes and remained at this pressure until 16 minutes after he left the surface. The two minutes spent in descending are counted as equivalent to one minute on the bottom, so that the total virtual exposure to an excess pressure of 75 lbs. is 15 *minutes*. For reasons which will be explained below the most rapid rate of saturation which need be considered corresponds to half saturation in 5 minutes, and the slowest rate to half saturation in 75 minutes. It will be seen that at the most rapid rate the saturation after 16 minutes from surface corresponds to an excess pressure of 66 lbs. of air, and at the slowest rate to 10 lbs. The latter pressure is far too low to be capable of causing any trouble on decompression, and the same remark applies to parts which half saturate in 40 minutes, since these parts will at the end of 16 minutes only be saturated to 17½ lbs. Even with sudden decompression, therefore, we should expect no symptoms in man from the more slowly saturating parts of the body. As shown in Appendix I., the symptoms known as "bends" are due to too rapid decompression of the more slowly saturating parts. The occurrence of these relatively trifling symptoms affords a most useful warning to workers in caissons and tunnels at much lower pressures, but this warning is absent with divers going for short periods to great depths. Any symptom occurring in the case under consideration, would presumably be of a more serious character; experience in diving shows only too clearly that this is the case.

We have now to calculate how our diver may be brought up safely by stages in the minimum of time. If his body had been fully saturated with nitrogen, the first step would have been to bring him to half the absolute pressure, or to $\frac{75 + 15}{2} = 45$ lbs. absolute pressure, or 30 lbs. excess pressure —*i.e.*, to a depth of, say, 70 feet. Only the very rapidly saturating parts of his body, however, are very highly saturated; and these parts, which are probably incapable of causing any symptoms even if he suddenly blew up to surface, rapidly give off much of their excess of nitrogen during his ascent to the first stage. It is therefore well within the limits of safety to let him ascend at once to 50 feet from surface (23 lbs. pressure). In order to prevent all hurry and risk of overshooting the proper stop, we think it is desirable that a diver should not as a rule ascend more rapidly than about 1 foot per second. He should be stopped when the gauge indicates about 30 feet below the first stop. The air-supply should also be stopped, and the gauge tapped, while the diver slowly ascends to the first stop. It would, therefore, take him about 3 minutes to come up to 50 feet.

During these three minutes the mean pressure will be $\frac{75 + 23}{2} = 49$ lbs., and the effect will be about equivalent to 3 minutes exposure at 49 lbs., so that the more highly saturated parts of the body will diminish, and the less highly saturated parts increase, in saturation. Let us follow what must happen in the case of the most rapidly saturating parts, represented in the upper curve in Figure 21. During the three minutes of ascent to 50 feet from surface the air-pressure (49 lbs.) is 17 lbs. below the initial saturation pressure of the part in question. As explained on page 40, the tissues will desaturate at the same rate as they saturate, the excess pressure, positive or negative, being the same. In the case under consideration the tissues, with a given excess of pressure, will half saturate or half desaturate in 5 minutes. Hence, as shown graphically on Figure 21, they will desaturate to the extent of one-third in 3 minutes. In other words, they will desaturate to the extent of $\frac{17}{3}$ = about 6 lbs., or from 66 lbs. to 60 lbs. At 50 feet, or 22½ lbs., there is a stop of 2 minutes. The excess of pressure in the tissues is now 60 − 22½ = 37½, and during two minutes the tissues will become 24 per cent. desaturated. Now 24 per cent. of 37½ is about 9, hence the saturation in the tissues will diminish by 9 lbs., or from 60 to 51 lbs.; and it will now be quite safe to come up to 40 feet. The further stops are 3 minutes at 40 feet, 5 minutes at 30 feet, 7 minutes at 20 feet, and 10 minutes at 10 feet, as shown in the following table. The rates of desaturation, as calculated in a similar manner for both quickly and slowly saturating parts, are graphically represented on Figure 21. The stoppages are so calculated as to just prevent the saturation pressure in any part of the body from becoming more than double the air-pressure; the object being to prevent all risk of symptoms. The only exception is in the case of the last step from 10 feet to surface; but even in this case the highest saturation pressure is not allowed to exceed 18 lbs., which is a safe limit, as already explained.

During muscular exertion the rate of blood circulation in increased; and if a diver during his ascent did very little muscular work he might, in consequence of the diminished circulation, give off nitrogen at a slower rate than according to the above calculations. To guard against this possibility it is desirable that during the stoppages he should actively work with his arms and legs. This precaution was taken in the experimental dives of Lieutenant Damant and Mr. Catto, and can easily be carried out.

Two tables have been constructed showing the stoppages required after dives to various depths and with various periods of stay on the bottom. The first table refers to ordinary limits of stay on the bottom, the limits being such that a diver can always return to surface safely within about half an hour at most, and might return by stages much more rapidly without serious risk.* The second table is for longer periods on the bottom. A diver might get foul of something on the bottom, and thus be unable to return within the limit of time specified in the first table; or for some other reason it might be necessary for him to remain for an extra long time. The table provides for enforced stays of any duration, but as the time needed to reach surface without risk of even slight symptoms, such as "bends," is very long, and the risks from exhaustion and cold during the process have to be considered, the stoppages during the ascent after the longest exposures are only sufficiently long to prevent any serious symptom of caisson disease from occurring. Both human experience and the experiments on goats show that with long exposures to pressure a rate of decompression can be selected which is sufficient to prevent any serious symptom, but not sufficient to prevent "bends" occurring. The precaution of exercising the limbs during the stoppages will, however, probably reduce the risk of bends. The experience of Drs. Hill and Greenwood (p. 37, above) points distinctly in this direction.

If the diver cannot exercise his limbs, or if he is of heavy build owing to excess of fat in his body, the stoppages should be fully a third longer if possible.

Figure 22 shows the calculated rate and extent of saturation of different parts of a diver's body with nitrogen when the descent to, and ascent from 28 fathoms are conducted according to the method previously recommended in the Diving Manual, the rate of descent and ascent being 12 fathoms in 15 minutes, and the time on the bottom being 14 minutes, as in the example already discussed. The time spent under water is 84 minutes, as against 46 by the new method with an equal time on the bottom; and it will be seen at once that the risks of death or very serious symptoms by the old method would be very great, as when the diver reaches the surface some parts (and probably the most dangerous ones) of his body would be still saturated to as much as 36 lbs. pressure. It would probably be hardly less

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* If, for instance, a pipe gave way, or anything else went wrong, he might come up, or be hauled up, with the stoppages reduced to half their usual length, and the first one or two omitted. The diminution of pressure would counteract the effects of the increasing percentage of CO_2 in the air of the helmet and dress. The defect should meanwhile be remedied if possible without delay, and the diver sent down again for a short distance, and brought up by stages.

safe to go straight to the bottom and come straight up after 14 minutes. Comparison of Figures 21 and 22 shows at a glance the great advantages gained by descending rapidly and ascending by the stage method. With the slow descent the diver's body is already almost as highly saturated when he reaches the bottom as it is after the whole stay on the bottom with the quick descent. With the uniform decompression most of the diver's body continues to increase in saturation during half the ascent or more; while with stage decompression the saturation rapidly diminishes from the outset.

As illustrating the risks involved in the current method of descent and ascent, even when the time on the bottom does not exceed 30 minutes, at a depth of only 20 fathoms, we may relate the following recently reported experience of five divers of H.M.S. "Diana" during operations for the recovery of an anchor and three shackles of cable in about 20 fathoms of water at Lagos. The work was carefully superintended, and the descent and ascent were carried out in close accordance with the recommendations of the Diving Manual. The times were noted, and were as follows:—

—	Going down.	Coming up.	On bottom.
21.2.07.			
Diver A - - -	29 34	34 39	30 32
" B - - -	30	37	30
" C - - -	32	38	20
" D - - -	33	37	30
" E - - -	28	34	30
22.2.07.			
Diver B - - -	25	35	30
" E - - -	30	36	30
" C - - -	29	36	25

Of the five divers, A suffered after his second descent from nausea and vomiting, which, however, soon passed off, and may have been due only to the excessive pressure of CO_2 in the air of the helmet, from the inadequate air supply. Diver D shortly after his ascent developed symptoms (faintness, dizziness, &c.) pointing distinctly to serious blockage of the circulation by bubbles in the heart. Diver E developed similar symptoms after his second descent. Both were on the sick list for five or six days, but completely recovered.

It will be noted that the symptoms were, not the "bends" which are so common among workers in caissons, tunnels, &c., but of a far more threatening character. In framing the appended Tables we have kept clearly in view the fact that in the case of divers with comparatively short exposures to pressure the symptoms to be guarded against are much more serious than "bends."

Precautions with very short and very long Exposures, and with repeated Descents.

Both human experience and experiments on animals show that rapid decompression is practically safe, even from pressures greatly exceeding 20 lbs., if the period of exposure is sufficiently short; for instance, there seems to be hardly any risk in rapid decompression after an exposure of half an hour at 30 lbs., or 15 minutes at 45 lbs. Some parts of the body (for instance, the grey matter of the Medulla, where the respiratory centre is situated) are probably practically saturated within a minute; and many other parts with a rapid circulation must be more that half saturated within five minutes.* It would seem, therefore, that these parts give rise to no risk in rapid decompression to a fourth of the absolute pressure, or even less. They desaturate so rapidly that there is not sufficient time for the formation

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* By determinations of the free nitrogen present in urine secreted during exposure to compressed air Hill and Greenwood have recently shown that this is the case for the human kidney during very active secretion (*Proc. Royal Society*, B., Vol. 79. 1907).

of bubbles in the blood passing through them. The fact that except with enormous pressures it is impossible to produce any symptoms at all in very small animals by rapid decompression, points distinctly in the same direction. In general, the more slowly any part of the body de-saturates the more likely it is to cause symptoms if the saturation has been sufficient. Even with decompressions to as far as a quarter of the absolute pressure it seems superfluous to take any account of parts which become half saturated in less than five minutes, particularly with a rate of ascent of only about 30 feet per minute, as recommended in the Tables. With decompressions to as far as a third, it is also superfluous to allow for parts which half saturate in less than ten minutes.

In the case of very long exposures to compressed air a different consideration applies. The experiments on goats indicate that in order to avoid all symptoms with these animals it is necessary to allow for parts of the body which become only half saturated in 45 minutes, and desaturate with corresponding slowness. Allowing for the difference in the rate of blood circulation between goats and men we should require, in order to avoid any symptoms in men of average build, to provide for parts of the body which take fully 1¼ hours to become half saturated or half desaturated.* But the only symptoms produced by the most slowly saturating and desaturating parts are, according to both human experience and the experiments on goats, "bends"; and these "bends" are of a very trifling character if the decompression has been so carried out as to avoid any more serious symptoms. Any diver would certainly sooner run a small risk of slight bends than undergo the exhausting process of being kept hanging on the shotted rope for a longer time than would otherwise be necessary. For this reason the stoppages in the Tables are only so calculated as to avoid the risk of anything more serious than "bends" after reaching the surface. The ideal spacing of the stoppages is, indeed, somewhat altered in order to avoid risk of "bends" under water.

The rates of decompression are all calculated as safe for the corresponding maximum pressures and maximum periods of exposure. For instance, at the greatest depths the decompression rate for "over 1 hour" is calculated as safe for a stay of any duration, so as to meet the case of a diver being so badly fouled that he cannot get free until the tide turns.

A diver has often to descend twice or oftener at short intervals. It is evident that at the beginning of the second descent the more slowly desaturating parts of the body will not have had time to lose their excess of nitrogen, and that consequently they will be more highly saturated at the end of the second stay on the bottom than would otherwise have been the case. This will be clear from a study of Figures 21 and 22. To meet the increased risk in decompression owing to this circumstance it is desirable, in calculating the proper rate of decompression, to add together the two periods of stay on the bottom, and adopt the corresponding rate of decompression. For the first half of the stoppages this is not necessary, but for the second half, including, of course, the longer stoppages required to meet the case of the more slowly desaturating parts, the rule should be carried out. Reference has already been made to the increasing danger experienced by pearl divers after successive dives without any precautions in decompression. This danger does not mount up to the same extent if stage decompression be used; but nevertheless exists.

As the interval of time between two successives dives increases the extra danger in decompression diminishes. With an hour's interval the extra precautions in decompression might be halved, and with two hours' interval they might be entirely omitted.

In general, the precautions recommended in the Tables are greatly in excess of those which have hitherto been commonly employed in either diving or work in caissons, tunnels, &c. We have endeavoured to leave a clear margin beyond anything which either human experience or experiments on animals, or calculation, has shown to be risky; and fortunately it has

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* For men of heavy build, and inclined to obesity, this allowance would be insufficient, and in the case of such men the stoppages during an ascent after a long exposure should be increased in length by a third, as already remarked.

been possible to do this with a clear saving of the time spent under water (with ordinary limits of working time) by divers at all depths, and a great increase in working efficiency and comfort. We have every reason to believe that if these precautions for divers, and the corresponding ones for other workers in compressed air, are carried out, the risks to life and health from caisson disease will practically disappear.

TABLE I.

Stoppages during the Ascent of a Diver after ordinary Limits of Time from Surface.

Depth.		Pressure.	Time from Surface to beginning of Ascent.	Approximate Time to First Stop.	Stoppages in Minutes at different Depths.						Total Time for Ascent in Minutes.
Feet.	Fathoms.	Pounds per square inch.			60 Ft.	50 Ft.	40 Ft.	30 Ft.	20 Ft.	10 Ft.	
0–36	0–6	0–16	No limit	—	—	—	—	—	—	—	0–1
36–42	6–7	16–18½	Over 3 hours	1	—	—	—	—	—	5	6
42–48	7–8	18½–21	Up to 1 hour	—	—	—	—	—	—	—	1½
			1–3 hours	1½	—	—	—	—	—	5	6½
			Over 3 hours	1½	—	—	—	—	—	10	11½
48–54	8–9	21–24	Up to ½ hour	—	—	—	—	—	—	—	2
			½–1½ hours	2	—	—	—	—	—	5	7
			1½–3 hours	2	—	—	—	—	—	10	12
			Over 3 hours	2	—	—	—	—	—	20	22
54–60	9–10	24–26½	Up to 20 mins.	—	—	—	—	—	—	—	2
			20–45 mins.	2	—	—	—	—	—	5	7
			¾–1½ hours	2	—	—	—	—	—	10	12
			1½–3 hours	2	—	—	—	—	5	15	22
			Over 3 hours	2	—	—	—	—	10	20	32
60–66	10–11	26½–29½	Up to ¼ hour	2	—	—	—	—	—	—	2
			¼–½ hour	2	—	—	—	—	—	5	7
			½–1 hour	2	—	—	—	—	3	10	15
			1–2 hours	2	—	—	—	—	5	15	22
			2–3 hours	2	—	—	—	—	10	20	32
66–72	11–12	29½–32	Up to ¼ hour	2	—	—	—	—	—	2	4
			¼–½ hour	2	—	—	—	—	3	5	10
			½–1 hour	2	—	—	—	—	5	12	19
			1–2 hours	2	—	—	—	—	10	20	32
72–78	12–13	32–34½	Up to 20 mins.	2	—	—	—	—	—	5	7
			20–45 mins.	2	—	—	—	—	5	10	17
			¾–1½ hours	2	—	—	—	—	10	20	32
78–84	13–14	34½–37	Up to 20 mins.	2	—	—	—	—	—	5	7
			20–45 mins.	2	—	—	—	—	5	15	22
			¾–1½ hours	2	—	—	—	—	10	20	32
84–90	14–15	37–40	Up to 10 mins.	2	—	—	—	—	—	3	5
			10–20 mins.	2	—	—	—	—	3	5	10
			20–40 mins.	2	—	—	—	—	5	15	22
			40–60 mins.	2	—	—	—	3	10	15	30
90–96	15–16	40–42½	Up to 10 mins.	3	—	—	—	—	—	3	5
			10–20 mins.	3	—	—	—	—	3	5	10
			20–35 mins.	2	—	—	—	—	5	15	22
			35–55 mins.	2	—	—	—	3	10	15	30
96–108	16–18	42½–48	Up to 15 mins.	3	—	—	—	—	3	5	11
			15–30 mins.	3	—	—	—	3	7	10	23
			30–40 mins.	3	—	—	—	5	10	15	33
108–120	18–20	48–53½	Up to 15 mins.	3	—	—	—	2	3	7	15
			15–25 mins.	3	—	—	—	5	5	10	23
			25–35 mins.	3	—	—	—	5	10	15	33
120–132	20–22	53½–59	Up to 15 mins.	3	—	—	—	2	5	7	17
			15–30 mins.	3	—	—	—	5	10	15	33
132–144	22–24	59–64½	Up to 12 mins.	3	—	—	—	3	5	5	16
			12–25 mins.	3	—	—	2	5	10	12	22
144–156	24–26	64½–70	Up to 10 mins.	3	—	—	—	2	5	5	16
			10–20 mins.	3	—	—	2	5	10	12	32
156–168	26–28	70–75	Up to 10 mins.	3	—	—	2	3	5	5	15
			10–16 mins.	3	—	2	3	5	7	10	30
168–180	28–30	75–80½	Up to 9 mins.	3	—	—	2	3	5	5	15
			9–14 mins.	3	—	2	3	5	7	10	30
180–192	30–32	80½–86	Up to 13 mins.	3	—	2	2	5	7	10	30
192–204	32–34	86–91½	Up to 12 mins.	3	2	2	3	5	7	10	32

TABLE II.

Stoppages during the Ascent of a Diver after delay beyond the ordinary Limits of Time from Surface.

Depth.		Pressure. Pounds per Square Inch.	Time from Surface to beginning of Ascent.	Approximate Time to First Stop.	Stoppages in Minutes at different Depths.								Total Time for Ascent in Minutes.
Feet.	Fathoms.				80 Ft.	70 Ft.	60 Ft.	50 Ft.	40 Ft.	30 Ft.	20 Ft.	10 Ft.	
60–66	10–11	26½–29½	Over 3 hours	2	—	—	—	—	—	—	10	30	42
66–72	11–12	29½–32	2–3 hours -	2	—	—	—	—	—	—	10	30	42
			Over 3 hours	2	—	—	—	—	—	—	20	30	52
72–78	12–13	32–34½	1½–2½ hours -	2	—	—	—	—	—	—	20	25	47
			Over 2½ hours	2	—	—	—	—	—	—	30	30	63
78–84	13–14	34½–37	1½–2 hours -	2	—	—	—	—	—	—	15	30	47
			2–3 hours -	2	—	—	—	—	—	5	30	30	67
			Over 3 hours	2	—	—	—	—	—	10	30	35	77
84–90	14–15	37–40	1–1½ hours -	2	—	—	—	—	—	5	15	25	47
			1½–2½ hours -	2	—	—	—	—	—	5	30	35	72
			Over 2½ hours	2	—	—	—	—	—	20	35	35	92
90–96	15–16	40–42½	1–1½ hours -	2	—	—	—	—	—	5	15	30	52
			1½–2½ hours -	2	—	—	—	—	—	10	30	35	77
			Over 2½ hours	2	—	—	—	—	—	30	35	35	102
96–108	16–18	42½–48	40–60 minutes	2	—	—	—	—	—	10	15	20	47
			1–2 hours -	2	—	—	—	—	5	15	25	35	82
			Over 2 hours	2	—	—	—	—	15	30	35	40	122
108–120	18–20	48–53½	35–60 minutes	2	—	—	—	—	5	10	15	25	57
			1–2 hours -	2	—	—	—	—	10	20	30	35	97
			Over 2 hours	2	—	—	—	—	30	35	35	40	142
120–132	20–22	53½–59	½–¾ hours -	3	—	—	—	—	5	10	15	20	53
			¾–1½ hours -	3	—	—	—	5	10	20	30	30	98
			Over 1½ hours	3	—	—	—	15	30	35	40	40	163
132–144	22–24	59–64½	25–45 minutes	3	—	—	—	3	5	10	15	25	61
			¾–1½ hours -	3	—	—	—	10	10	20	30	35	108
			Over 1½ hours	3	—	—	—	30	30	35	40	40	178
144–156	24–26	64½–70	20–35 minutes	3	—	—	—	3	5	10	15	20	56
			35–60 minutes	3	—	—	—	7	10	15	30	30	95
			Over 1 hour -	3	—	—	20	25	30	35	40	40	193
156–168	26–28	70–75	15–30 minutes	3	—	—	—	3	5	10	15	20	56
			½–1 hour -	3	—	—	3	10	10	15	30	30	101
			Over 1 hour -	3	—	5	25	25	30	35	40	40	203
168–182	28–30	75–80½	14–20 minutes	3	—	—	—	3	3	7	10	15	41
			20–30 minutes	3	—	—	2	2	3	10	15	25	60
			½–1 hour -	3	—	3	3	7	10	20	30	35	111
			Over 1 hour -	3	—	15	25	30	30	35	40	40	218
182–194	30–32	80½–86	13–20 minutes	3	—	—	—	3	3	7	15	15	46
			20–30 minutes	3	—	—	3	3	5	10	15	25	64
			½–1 hour -	3	—	3	5	10	12	20	30	35	118
			Over 1 hour -	3	5	20	25	30	30	35	40	40	228
194–206	32–34	86–91½	12–20 minutes	3	—	—	3	3	5	7	10	20	51
			20–30 minutes	3	—	3	3	3	5	10	20	20	67
			½–1 hour -	3	3	3	5	10	15	20	30	35	124
			Over 1 hour -	3	15	20	25	30	30	35	40	40	238

APPENDICES.

I.—Notes on Experiments made at the Lister Institute during June and July 1906, by A. E. Boycott, M.D., Fellow of Brasenose College, Oxford, and Lieutenant G. C. C. Damant, R.N., H.M.S. "Excellent."

II.—A Diary of the Deep Diving Experiments carried out off Rothesay, Isle of Bute, from H.M.S. "Spanker," August 1906.

III.—A suggested Method for the Better Testing of Diving Pumps.

Appendix I.

NOTES ON EXPERIMENTS MADE AT THE LISTER INSTITUTE DURING 1906 AND 1907, BY A. E. BOYCOTT, M.D., FELLOW OF BRASENOSE COLLEGE, OXFORD, AND G. C. C. DAMANT, LIEUTENANT R.N., H.M.S. "EXCELLENT."

During June and July 1906 a series of experiments on goats and men were made in the pressure chamber at the Lister Institute, as a preliminary to the diving experiments subsequently undertaken by Lieutenant Damant and Mr. Catto under similar circumstances. The experiments on goats have since then been greatly extended. While leaving a number of points for future elucidation they illustrate some of the more important principles of the causation and prevention of caisson disease, and a brief account of them is here given. Full details will shortly be published in the *Journal of Hygiene.*

The pressure chamber, which the Lister Institute owes to the munificence of Dr. Ludwig Mond, consists of a short segment of a boiler with curved steel plates at either end. Inside it is 8½ feet long, and 7 feet high and wide, and has a capacity of 336 cubic feet (9,500 litres). It is thus large enough to hold several persons comfortably, together with any apparatus which may be required. There are two doors; one, a manhole measuring 24 inches by 15 inches, is in common use, and is shown open in Figure 17. The other is much larger (28 × 24 inches), and is designed for the introduction of bulky apparatus; it is shown closed in Figure 16. A small air-lock shown in Figure 16 is provided, through which small articles may be passed during the progress of an experiment, while there are three observation windows. These consist of stout glass, but are also fitted with an automatic arrangement by which breakage of the glass causes a solid metal plug to fall into the hole. Compression or exhaustion was at first effected by a simple compressor driven by a gas-engine, which will raise the pressure about 2 lbs. a minute. The pressure is adjusted and regulated by a number of valves. Besides arrangements for varying the inlet to the compressor, the chamber itself is fitted with four simple and four adjustable spring valves, several of which are seen in Figure 17. By this means, the most exact adjustment may be made both with positive and negative pressures, either from inside or outside. The largest valve allows the pressure to be reduced from 100 lbs. to atmospheric pressure in about one minute. The compressor and chamber are fitted with various spring pressure gauges, together with a barometer for negative and a mercurial manometer for low positive pressures. Within, the chamber is fitted with benches for apparatus or rest, a telephone, an electric heater, and several electrical points for lighting, driving a motor, and the like. Experiments have already been made on human beings at pressures varying from 8½ lbs. below to 80 lbs. above atmospheric pressure, and the apparatus has been found to be extremely satisfactory.

The animal experiments were throughout conducted on goats. These animals were selected as being the largest which could conveniently be dealt with, bearing in mind that a considerable number would be required. The questions under consideration depend in a very fundamental way on the relation between the rapidity and volume of the circulation and respiration and the mass of the tissues. The degree to which the circulating blood washes the air in the lungs on the one hand, and the tissues on the other hand, varies considerably in different animals. In general it may be stated that the rapidity with which the tissues of the body are brought into relation with the air in the lungs varies inversely with the size of the animal. We have no means of measuring directly the general activity of the circulation, but, taking the series of warm-blooded animals as a whole, there is no doubt that it is normally adjusted to correspond to the rapidity of the gaseous exchange. Now the extent of this gaseous exchange, which may be conveniently measured by the quantity of carbonic acid given off per unit of body weight in a given time, is a function of the ratio between the surface and the mass of any given animal. It is therefore larger in small animals. A mouse of 25 grammes weight, for example, produces about 8 grammes of carbonic acid per kilogramme of body weight per hour, a rat of 150 grammes about 4 grammes, a guinea-pig of 400 grammes about 1·4 grammes, a rabbit of 2,000 grammes about 1·0 grammes, a goat of 19,000 grammes about 0·8 grammes, and a man of 70,000 grammes about 0·45 grammes. It is clear therefore that a mouse will take up excess of air and become saturated at any given pressure much more quickly than a man, and at the same time will get rid of this excess more quickly, so that in experiments of moderate and long duration the mouse will appear to be much less susceptible to caisson disease than a man. In the same way it may be assumed that the goat takes up and discharges excess of air more quickly than man, roughly in proportion to the fact that his respiratory exchange (as was ascertained by a number of experiments made by us for this purpose) is one and a half to two times as great as that of man. At the same time it must be remembered that these comparisons are good only for the average of a series of individuals. There are some goats which are more susceptible to decompression symptoms than some men, and some rats which are more susceptible than some rabbits.

The following is an experiment which illustrates the difference between different animals. We may premise that other experiments have shown that similar circumstances of pressure and decompression would be inevitably fatal to goats. Fifty-nine mice (average weight 20 grammes), 12 small rats (35 grammes), 13 medium rats (85 grammes), 8 large rats (200 grammes), 10 guinea pigs (250 grammes) and 7 rabbits (2,000 grammes) were compressed to 72 lbs. positive in 10 minutes, left for one hour and then decompressed in 50 seconds. Of the 109 animals, the largest rabbit (weighing 2,800 grammes) and one guinea pig died; the others showed no definite symptoms, and all survived. In another series of experiments 23 mice, 10 small, 9 medium, and 6 large rats, 10 guinea pigs, 5 rabbits and 10 goats were exposed to 51 lbs. pressure for 3 hours and then decompressed quickly. Of the goats 2 died, 3 were seriously ill, 3 slightly ill and 2 showed no symptoms; the largest rabbit (weighing 2,900 grammes) died and the others showed no symptoms.

The escape of these small animals is due to the rapidity of their circulation and respiration; they are thus enabled to discharge the excess of air very quickly. If the mechanism by which this discharge is effected be arrested, bubbles appear in the bodies of small and large animals alike. Thus in one experiment a selection of animals was taken into the chamber and after half an hour's exposure to so low a pressure as 30 lbs. a mouse, a young rat, an old rat and a guinea pig were killed and the corpses decompressed by the schedule for men. On examination after reaching atmospheric pressure bubbles were found in the blood of all four animals.

Considerations such as these therefore determined the choice of the largest available animal for experimentation, so that the results could the more readily be transferred to man. It was indeed clear that experiments on quite small animals could only be translated into human experience by the introduction of a quantity factor of almost qualitative dimensions.

Goats also presented two further advantages. They are large enough to give plenty of symptoms on inappropriate decompression from quite low pressures (*e.g.*, 45 lbs. positive). Small animals such as mice, on the other hand, required to be exposed to pressures approximating to 100 lbs. positive to give many symptoms with the most severe decompression. Such pressures are approaching (with long exposures) dangerously near the point at which oxygen poisoning is liable to appear. The occurrence of this fatality would hopelessly vitiate the experimental examination of pure caisson disease. Goats are also animals in which slight symptoms may be detected with a fair amount of certainty. While they are not particularly intelligent and on the whole definitely insensitive to pain, they are in emotional relations to their animate and inanimate surroundings of a kind sufficiently delicate to enable those to whom they are familiar to diagnose with considerable accuracy any slight abnormalities which they may present.

Most of the experiments have been made at a pressure of either 75 lbs. (6 atmospheres absolute) as representing a deep diving pressure (28 fathoms) or 45 lbs. as representing the upper limit of work in caissons (17 fathoms). It was also desirable to keep well within the limits of oxygen pressure at which symptoms of oxygen poisoning might complicate the experiment. We found, for example, that of 7 goats exposed to 81 lbs. positive pressure in an atmosphere containing 36·5 per cent. of oxygen (= 35 lbs. oxygen pressure = 10½ atmospheres positive air pressure = 57 fathoms) one died of pneumonia while under pressure, five of the others were slightly ill and one showed no symptoms.

We have been able to distinguish five fairly definite and frequent symptoms of illness in the experimental animals. The smallest effect which can be observed finds expression in what is apparently a sensation of uneasiness in one or more limbs. Without evincing any signs of pain, the animal holds its leg—most commonly a fore leg—off the ground, and is clearly unwilling to rest much weight upon it. In our experience this is by far the commonest symptom; in the great majority of cases it passes off in a few hours. We have ventured to provisionally identify it with the "bends" of caisson workers. The symptom which follows next in order of severity is a temporary paralysis, lasting from a few minutes to one or two hours, and unaccompanied by any signs of general illness. It nearly always affects the hind limbs, as does also a much more serious form of paralysis, which is either partially or completely permanent. Respiratory distress and dyspnœa form a fourth group. These are very serious symptoms, and are often only the prelude to the fifth group, which include fatal results. Besides these, a few cases of indefinite severe illness have occurred, which are too various for classification. In a general way we have grouped the symptoms under three headings: (1) slight symptoms or "bends"; (2) serious symptoms (paralysis, &c.); and (3) death.

The exact causation of all these symptoms is not yet fully elucidated. Respiratory distress is an indication of obstruction to the heart and pulmonary circulation by bubbles in the blood; when these become churned into a froth in the right side of the heart the whole circulation practically comes to a standstill, and death from asphyxia follows. Post-mortem examination of the animals which have succumbed to this train of symptoms has borne out this interpretation. Examination of the nervous system of paralysed animals shows that the condition is due to a local obstruction of the circulation (presumably by bubbles) causing the well-known "softening" of the nervous tissues. The anatomical condition underlying "bends" is not at all clear. The synovial fluid in the joints is full of fine bubbles, but this explanation will hardly account for all the various pains in the limbs which are experienced by men.

The time relations to decompression of the onset of these symptoms bears out human experience. Any of them may ensue almost immediately. More commonly, however, we have been able to watch the remarkable period of delay. A goat may be decompressed, released from the chamber, run about in the yard, exhibit its voracious appetite, and fight its companions—all the while showing nothing abnormal. Yet a quarter of an hour later it may be dead, with its blood vessels and heart full of bubbles and froth.* The onset of those milder symptoms which we have called "bends" may not be detected for half an hour, or even more, after decompression. The significance of this period of delay is engaging our attention; preliminary experiments show that bubbles form more slowly after decompression in blood saturated at high pressures outside the body than in water, and it is possible that this is the explanation of at least most of the delay.

The first series of experiments on goats were made with the slow method of compression already mentioned. It was therefore impossible to examine accurately the effect of the duration of exposure in short experiments. This, and our ignorance of the results to be expected from goats, rendered the experiments somewhat barren as far as definitive results were concerned, and no further account of them will be given in this place. They served however to orientate the experiments which were subsequently made upon animals, and afforded a basis on which the personal experiments of Lieutenant Damant and Mr. Catto in the pressure chamber could be framed. These experiments were undertaken in July 1906 as a preliminary to actual diving, and an account of them is here given.

In the first three or four the decompression was controlled from inside the chamber; in the rest from outside. The subjects remained closed in the chamber for half an hour after each experiment, the engine being also kept running so that recompression could be at once begun if any serious symptom developed. In addition to the actual period of exposure to each pressure, we have noted the virtual period of exposure calculated on the assumption that about half the time occupied in compression must be added (*see* above, page 43).

In view of the results with goats, the occurrence of decompression symptoms seemed probable in the more severe experiments. No symptoms were, however, observed, except considerable itching of the skin of the fore-arms where it was uncovered. In the compressed air the well-known alteration in the voice, and corresponding abnormal sensations about the lips and mouth, were very marked at pressures exceeding 60 or 70 lbs. Lieutenant Damant experienced feelings of exhilaration or slight intoxication, but Mr. Catto could not detect anything similar.

I. July 25th. Actual exposure to 39 lbs. for 1 hour. Virtual exposure 69 minutes. Decompression in 24 minutes:—

Compressed to - - - -	39 lbs.	in 17 minutes.	
Waited at - - - -	39 ,,	for 60 ,,	
Decompressed to - - - -	9 ,,	in 7 ,,	24.
Waited at - - - -	9 ,,	for 5 ,,	
Decompressed to - - - -	4 ,,	in 1 ,,	
Waited at - - - -	4 ,,	for 9 ,,	
Decompressed to - - - -	0 ,,	in 2 ,,	

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* Compare the case of the diver recounted above, page 33.

II. July 26th. Actual exposure to 50 lbs., 27 minutes. Virtual exposure, 39 minutes. Started at 10.37 a.m. Decompression in 34 minutes:—

B.

Compressed to	50 lbs.	in	24 minutes.
Waited at	50 ,,	for	27 ,,
Decompressed to	17 ,,	in	4 ,,
Waited at	17 ,,	for	6 ,,
Decompressed to	13 ,,	in	1½ ,,
Waited at	13 ,,	for	3½ ,,
Decompressed to	9 ,,	in	2 ,,
Waited at	9 ,,	for	3 ,,
Decompressed to	4 ,,	in	2 ,,
Waited at	4 ,,	for	8 ,,
Decompressed to	0 ,,	in	4 ,,

III. Same day, 3.3 p.m. Exposure to 55 lbs. for 19 minutes. Virtual 33 minutes. Decompressed in 31 minutes:—

Compressed to	55 lbs.	in	28 minutes.
Waited at	55 ,,	for	19 ,,
Decompressed to	17 ,,	in	4 ,,
Waited at	17 ,,	for	5 ,,
,, ,,	13 ,,	,,	5 ,,
,, ,,	9 ,,	,,	5 ,,
,, ,,	4 ,,	,,	10 ,,
Decompressed from	4 to 0 ,,	in	2 ,,

The time taken for decompressing from 17 to 13 lbs., &c., was counted as time at 13 lbs.

IV. July 27th, 10.29 a.m. Exposure to 60 lbs. for 20 minutes. Virtual exposure 36 minutes. Decompression in 37½ minutes:—

Compressed to	60 lbs.	in	30½ minutes.
Waited at	60 ,,	for	20 ,,
Decompressed to	22 ,,	in	5 ,,
Waited at	22 ,,	for	5 ,,
Decompressed to	17 ,,	in	1 ,,
Waited at	17 ,,	for	4 ,,
Decompressed to	13 ,,	in	1½ ,,
Waited at	13 ,,	for	3½ ,,
Decompressed to	9 ,,	in	1 ,,
Waited at	9 ,,	for	4 ,,
Decompressed to	4 ,,	in	1½ ,,
Waited at	4 ,,	for	8½ ,,
Decompressed to	0 ,,	in	2½ ,,

V. Same day, 3.37 p.m. Exposure to 67 lbs. for 18 minutes. Virtual exposure 36 minutes. Decompression in 36 minutes:—

Compressed to	67 lbs.	in	36 minutes.
Waited at	67 ,,	for	18 ,,
Decompressed to	22 ,,	in	3 ,,
Waited at	22 ,,	for	5 ,,
Decompressed to	17 ,,	in	1 ,,
Waited at	17 ,,	for	4 ,,
Decompressed to	13 ,,	in	1 ,,
Waited at	13 ,,	for	4 ,,
Decompressed to	9 ,,	in	1 ,,
Waited at	9 ,,	for	4 ,,
Decompressed to	4 ,,	in	1½ ,,
Waited at	4 ,,	for	8½ ,,
Decompressed to	0 ,,	in	3 ,,

VI. July 30th, 10.57 a.m. Actual exposure at 74 lbs., 15 minutes. Virtual exposure 35 minutes. Decompression in 42 minutes:—

Compressed to	74 lbs.	in	39 minutes.
Waited at	74 ,,	for	15 ,,
Decompressed to	26 ,,	in	4 ,,
Waited at	26 ,,	for	5 ,,

Decompressed to - - - - 22 lbs. in 1 minute.
Waited at - - - - - 22 ,, for 4 minutes.
Decompressed to - - - - 17 ,, in 1½ ,,
Waited at - - - - - 17 ,, for 3½ ,,
Decompressed to - - - - 13 ,, in 1 ,,
Waited at - - - - - 13 ,, for 4 ,,
Decompressed to - - - - 9 ,, in 1 ,,
Waited at - - - - - 9 ,, for 4 ,,
Decompressed to - - - - 4 ,, in 1½ ,,
Waited at - - - - - 4 ,, for 8½ ,,
Decompressed to - - - - 0 ,, in 3 ,,

VII. July 31st, 11.0 a.m. Actual exposure to 80 lbs. for 12 minutes. Virtual exposure, 34 minutes. Decompression in 51 minutes:—

Compressed to - - - - 80 lbs. in 44 minutes.
Waited at - - - - - 80 ,, for 12 ,,
Decompressed to - - - - 31 ,, in 3 ,,
Waited at - - - - - 31 ,, for 5 ,,
Decompressed to - - - - 22 ,, in 1 ,,
Waited at - - - - - 22 ,, for 4 ,,
Decompressed to - - - - 18 ,, in 1 ,,
Waited at - - - - - 18 ,, for 4 ,,
Decompressed to - - - - 15 ,, in 3 ,,
Waited at - - - - - 15 ,, for 2 ,,
Decompressed to - - - - 13 ,, in 1 ,,
Waited at - - - - - 13 ,, for 4 ,,
Decompressed to - - - - 9 ,, in 1 ,,
Waited at - - - - - 9 ,, for 9 ,,
Decompressed to - - - - 4 ,, in 2 ,,
Waited at - - - - - 4 ,, for 8 ,,
Decompressed to - - - - 0 ,, in 3 ,,

In November fresh arrangements were made to secure more rapid compression. A series of compressed air coils were furnished by the Admiralty, which were charged up to 70 atmospheres with a high pressure two-stage compressor: at the same time a large steel bottle was filled at 180 atmospheres. The contents of these reservoirs were then discharged into the tank through appropriate connections, and in this way the pressure could be raised to 60 lbs. in four minutes and to 75 lbs. in six minutes, or a little less, instead of 39 minutes with the old pump. With the aid of this arrangement a further series of experiments on goats was undertaken. In all about 700 experiments were made on 49 goats, besides the experiments on men, and on numerous small animals.

The following account contains a summary notice of some of these which illustrate various important points. In each series the effects on the goats are classed under four headings, viz. (1) no obvious illness; (2) bends; (3) paralysis and other severe symptoms, and (4) death.

I.—*Experiments showing that a certain Minimum Pressure is required to give Symptoms in Goats, and that the Results vary with the pressure.*

Pressure in Lbs. positive.	Exposure in Minutes.	Decompression in Minutes.	No. of Goats.	No Symptoms.	Bends.	Severe Symptoms.	Death.
20	240	½–2 - - -	22	21	1	0	0
25	240	,, - - - -	23	21	2	0	0
30	60	10 uniform - - -	19	15	4	0	0
45	60	,, - - -	11	7	3	1	0
60	45	15 uniform - - -	4	1	3	0	0
75	15	31 uniform - - -	36	19	13	3	1
75	50	10 uniform - - -	4	0	0	0	4

These experiments show that the effects become more severe as the pressure increases, although the duration of exposure is at the same time diminished and the duration of decompression increased. It was necessary to arrange the experiments in this way to prevent an inconvenient mortality among the animals.

II.—*Experiments showing that the duration of Exposure to High Pressure is of great importance.*

Pressure 75 lbs. positive, reached in six minutes.

Exposure in Minutes to 75 lbs.	Decompression in Minutes.	No. of Goats.	No Symptoms.	Bends.	Severe Symptoms.	Death.
1	1	6	6	0	0	0
3	1	5	4	0	1	0
6	1	6	6	0	0	0
10	1	7	6	0	1	0
15	10 uniform	7	2	3	1	1
15	31 stages	34	29	5	0	0
30	„	23	12	8	3	0
60	„	22	15	4	3	0
120	„	9	0	7	1	1
240	„	3	2	1	1	1

These experiments show that goats have taken up enough air in 15 minutes to give severe symptoms or death on uniform decompression in 10 minutes, while, if the exposure is less than 10 minutes, nearly all the animals escape, even with sudden decompression. Note, too, that with short exposures and rapid decompression such symptoms as appear are more frequently severe, and that bends are proportionately less common than with longer exposures and slower decompressions. Beyond 15 minutes exposure the results are somewhat irregular, but on the whole there is a progressive increase of bad symptoms up to two hours exposure. The results after four hours exposure are about the same, so that it would appear that goats are practically saturated in rather more than two hours.

Pressure 45 lbs. positive.

Exposure in minutes.	Decompression in Minutes.	No. of Goats.	No Symptoms.	Bends alone.	Severe Symptoms.	Death.
15	1	15	14	1	0	0
30	1	15	12	3	0	0
60	1	14	10	4	0	0
120	1	10	4	2	4	0
60	10 uniform	11	7	3	1	0
120	„	11	6	4	1	0
240	„	11	6	4	1	0
480	„	11	6	3	2	0

These figures show that with a duration of exposure up to about ¾ hour, no severe symptoms follow even sudden decompression. The series with sudden decompression show that the results after two hours are much worse than after one hour. This is not clear from the series with 10 minutes decompression, which, however, shows that the results do not become distinctly worse even after eight hours exposure.

III.—*Experiments to showthat the duration of Decompression is of great importance.*

Pressure 75 lbs. positive, reached in six minutes.

Exposure.	Decompression.	No. of Goats.	No Symptoms.	Bends alone.	Severe Symptoms.	Death.
15	10 uniform	7	2	3	1	1
15	21 „	35	19	13	3	1
15	90 „	12	9	3	0	0
30	31 stages	23	12	8	3	0
30	68 „	14	14	0	0	0
120	21 „	9	0	7	1	1
120	92 „	19	15	3	1	0

IV.—*Experiments to show that the absolute range of pressure through which Decompression occurs is of less importance than the relative range of absolute pressure.*

Pressure in lbs. +	Exposure in Minutes.	Decompression to lbs. +	Fall of Pressure in lbs.	Relative reduction of absolute Pressure.	Duration of decompression.	No. of Goats.	No. Symptoms.	Bends.	Severe Symptoms.	Death.
75	180	24	51	2·3 : 1	1¾	10	10	0	0	0
51	180	0	51	4·4 : 1	¼	10	2	3	5	2
45	120	— 6	51	6·7 : 1	6	3	0	1	1	1
39	120	— 6	45	6·0 : 1	6	4	1	0	3	0
45	120	0	45	4·0 : 1	1	10	4	2	4	0

A sudden drop of about 50 lbs. from 75 lbs. + to 27 or 24 lbs. + has been made about 200 times altogether in the course of these experiments without producing any symptoms, and about two-thirds of the animals showed no symptoms at the end of the stage decompression. In the present series the animals were left for one hour at 24 lbs. and watched very carefully, and afterwards suddenly decompressed to 17 lbs. and again observed for one hour. The same goats were subsequently dropped suddenly from 51 lbs. + to atmospheric pressure with very disastrous results, and a drop of 51 lbs. from 45 lbs. + to − 6 lbs. was even worse.

V.—*Experiments showing the importance of the mode and spacing of Decompression.*

Each of the following six series of experiments was made upon the same goats, which were exposed to 75 lbs. positive pressure for varying periods, and then decompressed on the one hand by stages according to the principles which have been explained in the Report; and on the other hand at a uniform rate, the whole time being equal to that occupied in the stage decompression. The only exceptions to this are found (1) in Series E in which the uniform decompression was extended from 92 to 100 minutes in order to test the statement that uniform decompression at the rate of 20 minutes an atmosphere is safe; (2) in Series A 18 goats were each tested twice except that two animals did not experience the second test with stage decompression; one had died with uniform decompression and one was ill from an injury.

75 lbs. Positive Pressure.

Series.	Exposure in Minutes (in addition to 6 Minutes spent in compression).	Decompression in Minutes.	No. of Goats.	Stage Decompression.				Uniform Decompression.			
				No Symptoms = p.c.	Bends.	Severe Symptoms.	Death.	No Symptoms = p.c.	Bends.	Severe Symptoms.	Death.
A	15	31	34 stages, 36 uniform.	29 = 85	5	0	0	19 = 53	13	3	1
B	30	31	6	4 = 67	2	0	0	1 = 17	4	1	0
C	30	68	14	14 = 100	0	0	0	7 = 50	7	0	0
D	120	70	13	9 = 69	4	0	0	4 = 31	7	2	0
E	120	92	19	15 = 79	3	1*	0	10 = 53	3	5	1
F	180	133	10	8 = 80	2	0	0	5 = 50	5	0	0
	Total -	-	96 stages, 98 uniform.	79 = 82	16	1	1	46 = 47	39	11†	2

* Temporary partial paralysis (foot-drop) of one hind leg, passing off completely in an hour.

† Temporary paralysis in four cases; permanent paralysis in three cases; dyspnœa (from air in heart) in two cases; and severe obscure illness in two cases.

In each one of these six series, therefore, stage decompression shows better results than uniform decompression in an equal time. On the whole nearly twice as many (82 per cent. as against 47 per cent.) goats escaped illness with stage decompression as with uniform decompression,* and only one animal showed symptoms more serious than bends with the former method as compared with 11 cases of serious illness and 2 deaths with uniform decompression.

The experiments also show that the advantage of stage decompression becomes less marked as the duration of the exposure is increased. This is in full agreement with the theoretical considerations. With short exposures stage decompression has the advantage of shortening the exposure to high pressures as well as of increasing the nitrogen extracting stress: with long exposures any additional duration of exposure becomes relatively less important; and stage decompression is consequently less markedly superior to uniform decompression.

VI. *Experiments showing the bad effects of Slow Compression.*

Pressure 75 lbs. positive.

Time of Compression Minutes.	Exposure Minutes.	Decompression in Minutes.	Goats.	No Symptoms.	Bends.	Severe Symptoms.	Death.
30 - -	15	45 stages	10	5	5	0	0
6 - -	15	31 stages	34	29	5	0	0

---

* It must be noted that these experiments are not designed to show that these particular stage decompressions are safe: with the exception of series C and F, all the stage decompressions were intentionally framed to give some symptoms. As a rule a decompression was used which had been calculated as being appropriate to an exposure somewhat shorter than that actually given.

These experiments show that, with short exposures, the results are three times as bad when 39 minutes is occupied in raising the pressure to 75 lbs. as when this point is reached in 6 minutes, although the animals were in the latter case subsequently decompressed in two-thirds of the time occupied in the former series.

One of the most striking features in all the animal experiments has been the great variability of the results. This variability is not different from that which has always been noted among caisson-workers. The tables show that under all the circumstances examined a proportion of the animals showed no symptoms. It is not easy to accurately define whether the susceptibility of the different animals to symptoms was temporary or permanent. We were, however, able to satisfy ourselves that certain goats were habitually relatively immune. It is a matter of the greatest interest to determine the basis of this varying susceptibility. In our animals it was certainly not altogether a question of age or size, for the largest, oldest and fattest goat ("Pa") was very resistant, while one of the smallest and thinnest animals ("Little Billy") was soon prostrated with paralysis by the same experiments. It seemed, on the other hand, that nanny goats were distinctly more susceptible to severe symptoms (death) than billy goats. The females have more lax abdominal walls and much more abdominal and subcutaneous fat than the males (*see* above, p. 58). The susceptibility to "bends" seemed about equal in the two sexes. We obtained some experimental evidence (not however of an altogether conclusive character) that the goats with the greatest respiratory exchange were less susceptible.

It is also of interest to note the incidence of the different symptoms. With moderate or long exposures both the proportion of animals showing illness and the severity of these illnesses are in relation to the rapidity and spacing of the decompression. But it appears likely that this only applies to animals which are fairly saturated or have taken up a material excess of gas. For if sudden decompression ensues immediately on, or very shortly after, reaching 75 lbs. pressure, the animals show severe symptoms or none at all.

Pressure 75 lbs. positive.

Compression in 5¼ to 6 minutes.

Actual exposure in Minutes.	Decompression in Minutes.	Goats.	No Symptoms.	Bends.	Severe Symptoms.	Death.
1 - -	1	6	6	0	0	0
3 - -	1	5	4	0	1	0
6 - -	1	6	6	0	0	0
10 - -	1	7	6	0	1	0
15 - -	1	6	2	2	1	1

The important conclusion is that "bends" do not follow such brief exposures to high pressures as may cause more severe symptoms. It follows that "bends" must be the expression of phenomena which are not necessarily identical with those which in a more exaggerated form cause paralysis and death, and that the occurrence of "bends" is an indication that a fair degree of saturation has been reached. The experiments are in agreement with the well-established fact that divers (with short exposures to high pressures) experience severe symptoms or none at all, while caisson-workers (with long exposures to lower pressures) suffer very frequently from "bends" and relatively seldom from paralysis or death. It seems justifiable to conclude that "bends" are the expression of the remoteness of the parts saturated rather than of the fact that saturation has occurred, and that when once those remote parts of the body have taken up a material excess of air, extremely slow decompression would be required to escape that symptom altogether. The practical consequence of this would be that bends are an indication of extreme danger if the exposure has not been long and the rate of decompression has been rapid, but that their significance is much less serious if the exposure has been long and the rate of decompression slow.

Appendix II.

A DIARY OF THE DEEP DIVING EXPERIMENTS CARRIED OUT OFF ROTHESAY, ISLE OF BUTE, FROM H.M.S. "SPANKER," AUGUST 1906.

Monday, 20th August.

H.M.S. "Spanker" arrived at Rothesay about 7 p.m., and was met by Drs. Haldane and Rees and Mr. Catto, Gunner R.N. Arrangements were made to commence experiments the following day.

Tuesday, 21st August.

All the pumps to be used in the experiments were tested up to a pressure of 200 feet, and the leakage at this pressure measured. The pressure gauges, which had been specially graduated for these experiments, were tested and found to give correct readings. The method of testing employed was to attach the free end of the diving hose to a lead line, and lower it over the side into the sea to the required depth. The pumps were then hove round until there was a free supply of air, and then stopped whilst the reading of the gauge was taken.

The re-compression chamber was tested on the Whitehead torpedo charging column, and it was found that the pressure could be brought up to 40 lbs. on the gauge in 3 minutes. There was a leak of 1 lb. per minute, or, roughly 3 cubic feet. Afterwards Drs. Haldane and Rees were compressed up to about 30 lbs. in order to further test the working of the chamber.

In the afternoon both divers made a trial dive in 15 fathoms:—

—	Lieutenant Damant.	Mr. Catto.
Time of descent - - -	2 minutes - - -	1½ minutes.
„ on bottom - - -	1 hour - - -	1 hour.
„ of ascent - - -	18¼ minutes - -	17½ minutes.
No. 5-minute stops - -	1 at 30 feet - - -	1 at 20 feet.
„ 10 „ „ - -	1 „ 10 „ - -	1 „ 10 „

Two double pumps were used for each diver in these and the subsequent dives. The divers were perfectly comfortable in moving about on the bottom. It may be mentioned that Lieutenant Damant had not dived previously beyond about 19 fathoms, and had no experience in diving except what he had gained in his course of instruction as a gunnery officer and in experimenting at Portsmouth for the Committee. Mr. Catto had much previous experience in diving work, but had never dived beyond 23 fathoms.

Wednesday, 22nd August,
H.M.S. "Spanker," off Rothesay.

In the forenoon Mr. Catto descended in 23 fathoms, and in the afternoon Lieutenant Damant did the same:—

—	Mr. Catto.	Lieutenant Damant.
Time of descent - - -	2 minutes - - -	2½ minutes.
„ on the bottom - - -	20 „ - -	20 „
„ of ascent - - -	35½ „ - - -	32½ „
No. 5-minute stops - - -	4 at 50, 40, 30, 20 feet -	2 at 50, 40 feet.
„ 10 „ „ - -	1 „ 10 feet - -	2 „ 20, 10 „

Thursday, 23rd August,
H.M.S. "Spanker," off Rothesay.

After testing the pumps each diver made a descent to 25 fathoms:—

—	Lieutenant Damant.	Mr. Catto.
Time of descent - - -	2 minutes - - -	2 minutes.
„ on the bottom - - -	18¾ „ - -	19¼ „
„ of ascent - - -	37½ „ - - -	39¾ „
No. 5-minute stops - - -	3 at 60, 45, 30 feet - -	3 at 50, 40, 30 feet.
„ 10 „ „ - -	2 „ 20, 10 feet - -	2 „ 20, 10 feet.

Friday, 24th August.

H.M.S. "Spanker" was taken through the narrows of the Kyles of Bute and anchored off the entrance of Loch Riddon.

In the morning, after the usual tests had been applied to the pumps, Mr. Catto descended in 27 fathoms, and in the afternoon Lieutenant Damant went down in a similar depth :—

—	Mr. Catto.	Lieutenant Damant.
Time of descent	2 minutes	1 minute 20 seconds.
,, on the bottom	16½ ,,	16¾ minutes.
,, of ascent	55½ ,,	44½ ,,
No. 5-minute stops	4 at 60, 50, 40, 30 feet	4 at 60, 50, 40, 30 feet.
,, 10 ,, ,,	1 at 20 feet. (Diver was employed just under the ship's bottom in examining a propeller which had been slightly injured, for 19½ minutes before coming up.)	2 ,, 20, 10 feet.

Saturday, 25th August,

H.M.S. "Spanker," off Loch Riddon.

The "Spanker" shifted her position slightly, and, after the usual tests of the pumps, both divers descended in 29 fathoms of water :—

—	Mr. Catto.	Lieutenant Damant.
Time of descent	3 minutes	1⅓ minutes.
,, on the bottom	14½ ,,	13½ minutes.
,, of ascent	46 ,,	48⅓ minutes.
No. 5-minute stops	4 at 70, 50, 40, 30 feet	4 at 66, 54, 40, 30 feet.
No. 10- ,, ,,	2 at 20, 10 feet	2 at 20, 10 feet.

Monday, 27th August,

H.M.S. "Spanker," of Loch Riddon.

Thirty fathoms of water were obtained. Mr. Catto was the diver in the morning. The pumps used were Nos. 3,604 and 3,593. Six men were told off for each pump, in reliefs of 5 minutes. Details of the descent :—

Time.	Remarks.
11.22	Glass screwed up. Depth by lead line 30½ fathoms.
11.23¼	Diver under water.
11.23½	,, down 50 feet.
11.23¾	,, ,, 70 ,,
11.24¼	,, ,, 110 ,,
11.24½	,, ,, 150 ,,
11.24¾	,, ,, 180 ,, on the bottom. 1 min. 30 secs. in descending. Revolutions averaged 32 per min., but fell to 24 for a short time, owing to the great exertions that were necessary to keep the pumps going at the higher speed. Diver quite comfortable while moving about on the bottom.
11.36¾	Diver called up.
11.38½	,, started up.
11.39¼	,, at 160 feet.
11.39¾	,, ,, 140 ,,
11.40¼	,, ,, 120 ,,
11.41	,, ,, 100 ,,
11.41½	,, ,, 70 ,, 1st stop. Diver employed in gymnastic exercises. One pump stopped.
11.46½	,, ,, 50 ,, 2nd stop.
11.51½	,, ,, 40 ,, 3rd stop.
11.56½	,, ,, 30 ,, 4th stop.
12.1½	,, ,, 20 ,, 5th stop.
12.11½	,, ,, 10 ,, 6th stop. There were no ill-effects. Water jackets gained 20 degrees F
12.22½	,, called up.
12.23¾	Glass off.

Afternoon.—Lieutenant Damant.

Time.	Remarks.
2.14½	Screwed up glass.
2.15¾	Diver under water.
2.16	,, down 70 feet.
2.16¼	,, ,, 120 ,,
2.16¾	,, ,, 160 ,,
2.17	,, ,, 186 ,, on the bottom. 1 minute 20 seconds in descending. Revolutions averaged 30 per minute.
2.29	Diver called up.
2.30	,, started up.
2.31	,, at 170 feet.
2.33	,, ,, 120 ,, Diver stopped 1¼ minutes.
2.33½	,, ,, 70 ,, 1st stop.

Time.	Remarks.
2.38½	Diver at 50 feet 2nd stop.
2.43½	,, ,, 40 ,, 3rd ,,
2.48½	,, ,, 30 ,, 4th ,,
2.53½	,, ,, 20 ,, 5th ,,
3.3½	,, ,, 10 ,, 6th ,,
3.13½	,, called up.
3.15¾	Glass off. There were no ill-effects. Later in the afternoon the pumps were tested at different temperatures of the water jacket, to see how the leakage was affected.

Tuesday, 28th August.

In the same locality, Lieutenant Damant made a second descent in 30 fathoms in order to obtain samples of the air in the helmet. The pumps used were Nos. 3,588 and 3592 :—

Time.	Remarks.
10.18½	Diver under water.
10.20¼	,, on the bottom, 1 minute 40 seconds in going down.
10.34½	,, started up.
11.21½	Glass off. Whilst on the bottom, diver took two samples whilst at rest. There was a distinct tide on the bottom, which affected the diver.

Analysis of Samples.

No. of Sample.	C.O.$_2$ per Cent.	O$_2$ per Cent.	CO$_2$ Production in Cubic Feet per Minute.
1st - -	·32	20·86	·025
2nd - -	·50	20·43	·041 (? tide.)

In the afternoon Mr. Catto was in the dress. Pumps Nos. 3,588 and 3,592 were used :—

Time.	Remarks.
2.17	Glass screwed up.
2.18¾	Diver down 60 feet.
2.19	,, ,, 100 ,,
2.19¾	,, ,, 180 ,, on the bottom. The diver took down with him a wire hawser to shackle on to a sinker.
2.31½	Diver called up, but could not come up as he was foul, until —
2.48½	,, started up.
2.50½	,, at 140 feet.
2.53	,, ,, 100 ,, 1st stop.
2.56	,, ,, 80 ,, 2nd ,,
3.1	,, ,, 60 ,, 3rd ,,
3.7	,, ,, 50 ,, 4th ,,
3.12	,, ,, 40 ,, 5th ,,
3.22	,, ,, 30 ,, 6th ,,
3.37	,, ,, 20 ,, 7th ,,
3.52	,, ,, 15 ,, 8th ,,
4.0	,, ,, 10 ,, 9th ,,
4.18½	,, on the surface.

Mr. Catto attempted to shackle a hawser on to the sinker. He found the sinker without the slightest difficulty, and then, having tied his distance line to it, went back to the hawser. He found this in bights, and he seems to have got within the coils, and in trying to find the end of the wire to have fouled his life line. When called up he could not get away, and it was 20 minutes before he could clear himself. In all he was down 28¾ minutes in 30 fathoms of water. The rate of the pumps could not be kept up above 24 revolutions per minute, and the supply of air was not adequate to his exertions to free himself, so that he was almost overcome by the excess of CO$_2$. On account of his long exposure during heavy work, great care was taken in decompressing him, 1¾ hours being allowed. There were no ill-effects.

Thursday, 30th August.

H.M.S. "Spanker, off Loch Riddon.

Mr. Catto made another descent under the same conditions, and shackled on the hawser to the sinker in 4 minutes after reaching the bottom. The revolutions of the pump averaged 24 to 30 per minute. The day was very bright, with the sun shining on the water, so that the diver saw with comparative ease in the water.

In the afternoon Lieutenant Damant, at the same depth, took three samples of the air in the helmet, and the pumps were tested at 180 feet pressure. He suffered from no ill-effects:—

—	Mr. Catto.	Lieutenant Damant.
Time of descent	3 minutes	1 min. 20 secs.
,, on the bottom	12¾ ,,	13 minutes.
,, of ascent	46½ ,,	46¼ ,,
No. 5-minute stops	4 at 70, 50, 40, 30 feet	4 at 70, 50, 40, 30 feet.
,, 10 ,,	2 at 20, 10 feet	2 at 20, 10 feet.

Analysis of Samples obtained by Lieutenant Damant.

Per Cent.	First Sample.	Second Sample.	Third Sample.
CO_2	·43	·39	·36
O_2	20·56	20·52	20·47
Deficiency of oxygen	·43	·52	·57
CO_2 produced in cubic feet per minute	·035	·029	·027

Friday, 31st August.

H.M.S. "Spanker" moved down to the entrance of Loch Striven, where 35 fathoms of water could be obtained.

In the morning Lieutenant Damant was the diver. Pumps Nos. 2,593, 3,604, and 3,592 were tested and used. Six hands were told off for each pump in reliefs of 5 minutes:—

Time.	Remarks.
11.8	Glass screwed up.
11.8½	Diver under water.
11.9	,, down 80 feet.
11.9¼	,, ,, 120 ,,
11.9½	,, ,, 150 ,,
11.9¾	,, ,, 180 ,,
11.10¼	,, ,, 200 ,,
11.10½	,, ,, 216 ,, on the bottom. Revolutions kept at 30 per minute, and the diver had a good supply of air.
11.13½	Diver took samples seated on the shot at the bottom of the rope.
11.15½	,, called up.
11.16¼	,, started up.
11.17	,, at 190 feet.
11.18	,, ,, 110 ,, Diver stopped to blow off sampling tube.
11.20½	,, ,, 90 ,, 1st stop.
11.23½	,, ,, 70 ,, 2nd ,,
11.28¼	,, ,, 52 ,, 3rd ,,
11.33¼	,, ,, 42 ,, 4th ,,
11.39¼	,, ,, 32 ,, 5th ,,
11.44½	,, ,, 22 ,, 6th ,,
11.54½	,, ,, 11 ,, 7th ,,
12.4½	,, called up.

There was no light on the bottom, which was of soft mud. The depth by the shot line was 210 feet. Pressure was 93¼ lbs. The gauge showed a pressure of 216 feet of fresh water with the pumps stopped, and 220 feet whilst they were heaving. The actual depth, as carefully measured on the shotted rope against the ship's standard measure, was just over 35 fathoms, 210 feet.

In the afternoon Mr. Catto made the same descent, and reached 35 fathoms. He found that the air supply was more than ample. He walked out to the end of his distance line, and then took a sample of the air in his helmet:—

Time.	Remarks.
2.12	Screwed up glass. Same pumps as last.
2.12¾	Diver under water.
2.14¾	,, on the bottom. Revolutions reduced to 24, as the diver found the supply too much. He proceeded to the end of his distance line before taking his sample.
2.20½	Diver started up.
2.27¾	,, at 90 feet. 1st stop.
2.30½	,, ,, 70 ,, 2nd ,,
2.35¾	,, ,, 50 ,, 3rd ,,
2.40¾	,, ,, 40 ,, 4th ,,
2.45¾	,, ,, 30 ,, 5th ,,
2.50¾	,, ,, 20 ,, 6th ,,
3.0¾	,, ,, 10 ,, 7th ,,
3.10¾	,, called up.

Analysis of Samples.

	Lieut. Damant.	Mr. Catto.
CO_2 per cent.	·14	·53
O_2 ,, ,,	20·89	20·34
Deffciency of O_2 per cent.	·15	·70

Monday, 3rd September.

Experiments on rest and measured work were carried out, by means of the apparatus figured in the text. This consisted of a length of line which was carried under a fixed block attached to a 200-lb. sinker, and over fixed blocks attached to a spar projecting over the ship's side. At the sinker end a light spar formed a handle, whilst at the other end a 56-lb. sinker was attached. The diver could stand on the shot and pull on the handle with both hands, so raising the weight:—

Time.	Remarks.	
2.26	Diver, Mr. Catto, descended.	
2.27½	,, on bottom, 142 feet.	
2.31	,, took sample sitting on the shot.	(No. 1.)
	Two pumps at 30 revolutions per minute.	
	Raised the weight 4 times 5 feet, at the rate of one lift per minute.	
2.36	,, took sample.	(No. 2.)
	Raised weight 7 times 5 feet in 5¼ minutes.	
2.42	,, took sample.	(No. 3.)
2.45	,, started up.	
3.23	,, on surface, no ill effects.	
3.3½	,, Lieutenant Damant, started down.	
3.4½	,, down 100 feet.	
3.5	,, on bottom, 139 feet.	
4.0	,, took sample sitting on the shot.	(No. 4.)
	Two pumps at 26 revolutions.	
	Raised weight 5 times in 1¾ minutes.	
4.3	,, took sample.	(No. 5.)
	Raised weight 5 feet 18 times in 6½ minutes.	
4.10	,, took sample. Pump 24 revolutions.	(No. 6.)
4.13½	,, started up.	
4.52½	,, at the surface. No ill-effects.	

Analysis of Samples.

CO_2	·30	per cent.	Mr. Catto.	Sample No. 1.
O_2	20·72	,,		
CO_2	·70	,,	,,	,, No. 2.
O_2	20·29	,,		
CO_2	·71	,,	,,	,, No. 3.
O_2	20·23	,,		
CO_2	·18	,,	Lieutenant Damant.	Sample No. 4.
O_2	20·73	,,		
CO_2	·73	,,	,,	,, No. 5.
O_2	20·12	,,		
CO_2	·81	,,	,,	,, No. 6.
O_2	20·36	,,		

Tuesday, 4th September.

The "Spanker" was anchored in 6 fathoms of water, and experiments were made on the bottom by Dr. Haldane, Lieutenant Damant, and Mr. Catto on the risks of blowing up. After being compressed in the air chamber to teach them to open their Eustachian tubes, Lieutenant and Commander E. V. F. R. Dugmore, Lieutenant G. N. Henson, Jack Haldane (age 13) all made descents in 6 fathoms of water. This was the first time that these had ever dived in a diving dress, which illustrates the usefulness of the re-compression chamber in the practical teaching of divers.

Wednesday, 5th September.

Exhaustive tests were made as to the leakage of the pumps and composition of the air, with the water jackets at various temperatures. The results are embodied in the Report. These experiments concluded the work undertaken for the Committee.

Appendix III.

A SUGGESTED METHOD FOR THE BETTER TESTING OF DIVING PUMPS.

The following method of testing the leakage in the diving pumps has been tested in H.M.S. "Dreadnought," and is suggested for use in His Majesty's ships.

The diving pump should be connected by means of a length of flexible metal hose to a group of air bottles, or torpedo charging columns, of known capacity. It will be necessary to provide an adapter piece for this purpose. The pumps should be tested one cylinder at a time, and the number of revolutions required to bring the pressure in the bottles, as indicated on the diving pump pressure gauge, up to 15 lbs., 30 lbs., 45 lbs., 60 lbs. and so on, noted. From this the percentage leakage can be easily obtained, as the Service pump is calculated to deliver ·1 cubic foot per revolution.

On board H.M.S. "Dreadnought" a group of air bottles having a cubic capacity of 10 feet was used, with the following results:—

Cylinder.	No. of Revolutions to give 10 Cubic Feet of Air, as measured by the Dry Gas Meter.	No. of Revolutions to give on the Diving Pressure Gauge.	Pressure in Lbs. per Square inch.
Left - - -	105 at 7 lbs. pressure - - - -	105	15
,, - - -	110 ,, 22 ,, ,, - - - -	116	30
,, - -	116½ ,, 37 ,, ,, - - - -	116	45
Right - - -	107 ,, 7 ,, ,, - - - -	118	15
,, - -	110 ,, 22 ,, ,, - - - - -	105	30
,, - - -	119 ,, 37 ,, ,, - - - -	120	45

It is to be observed that there was no correction for temperature or the capacity of the flexible lead, and that in the case of the gas meter the leakage is measured at the mean pressure. The results show a very satisfactory agreement between the gas meter method and the method of testing with the air-bottles and gauge.

ILLUSTRATIONS.

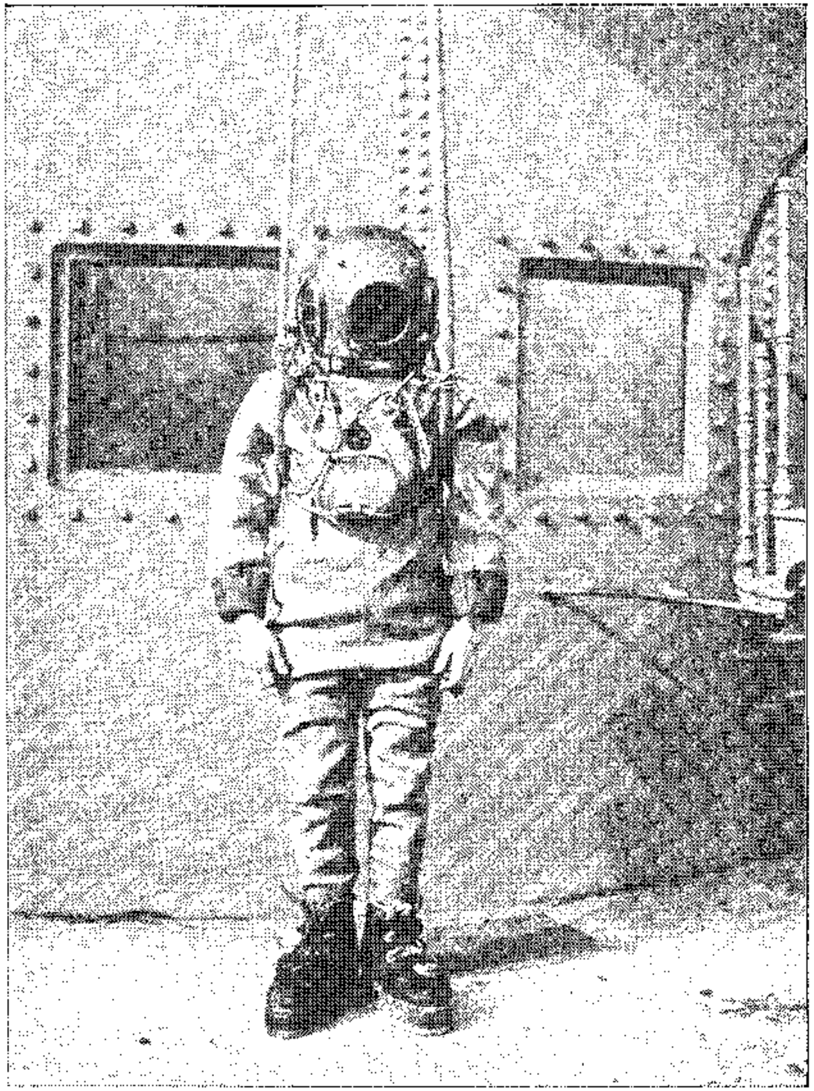


Fig. 1.—Diving dress, front view, with air-pipe and life-line attached. New pattern, with legs laced up. The extra tap, used for taking air-samples, is seen to the right of the front of the helmet.

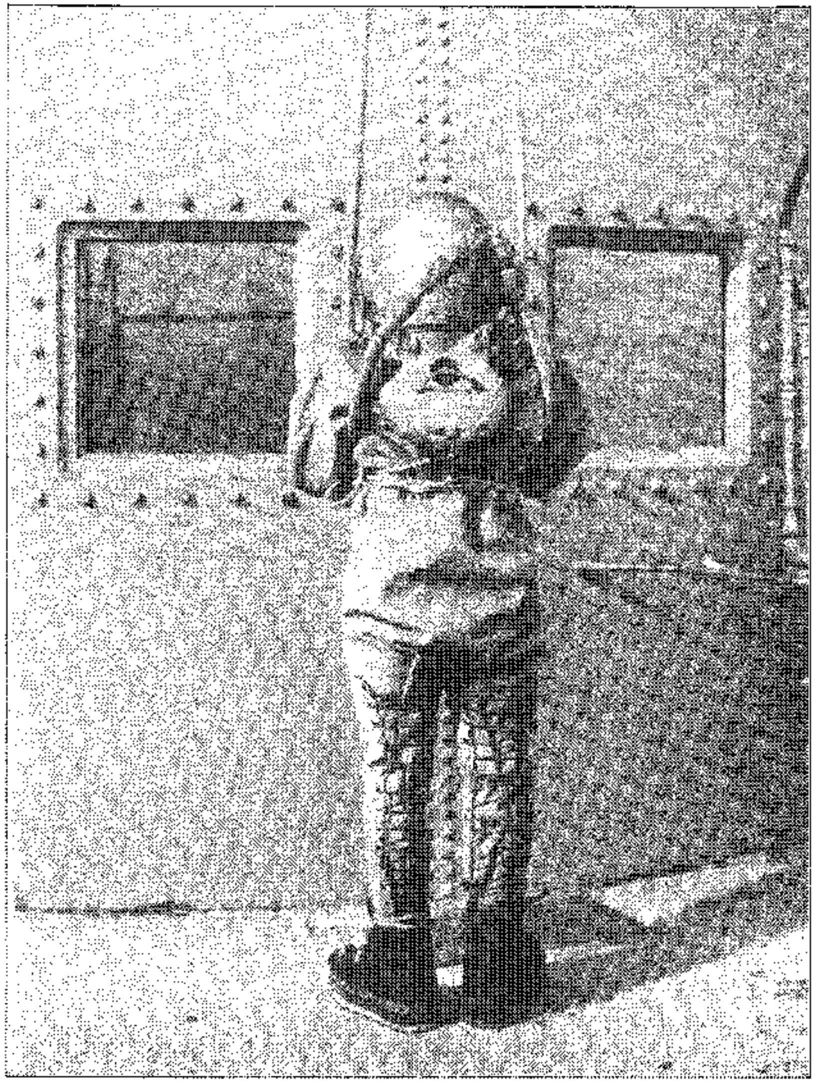


Fig. 2.—Diving dress, back view, showing attachment of air-pipe and life-line with telephone connection. New pattern, with legs laced up to prevent diver from being capsized and accidentally blown up to surface, or hung in a helpless position.

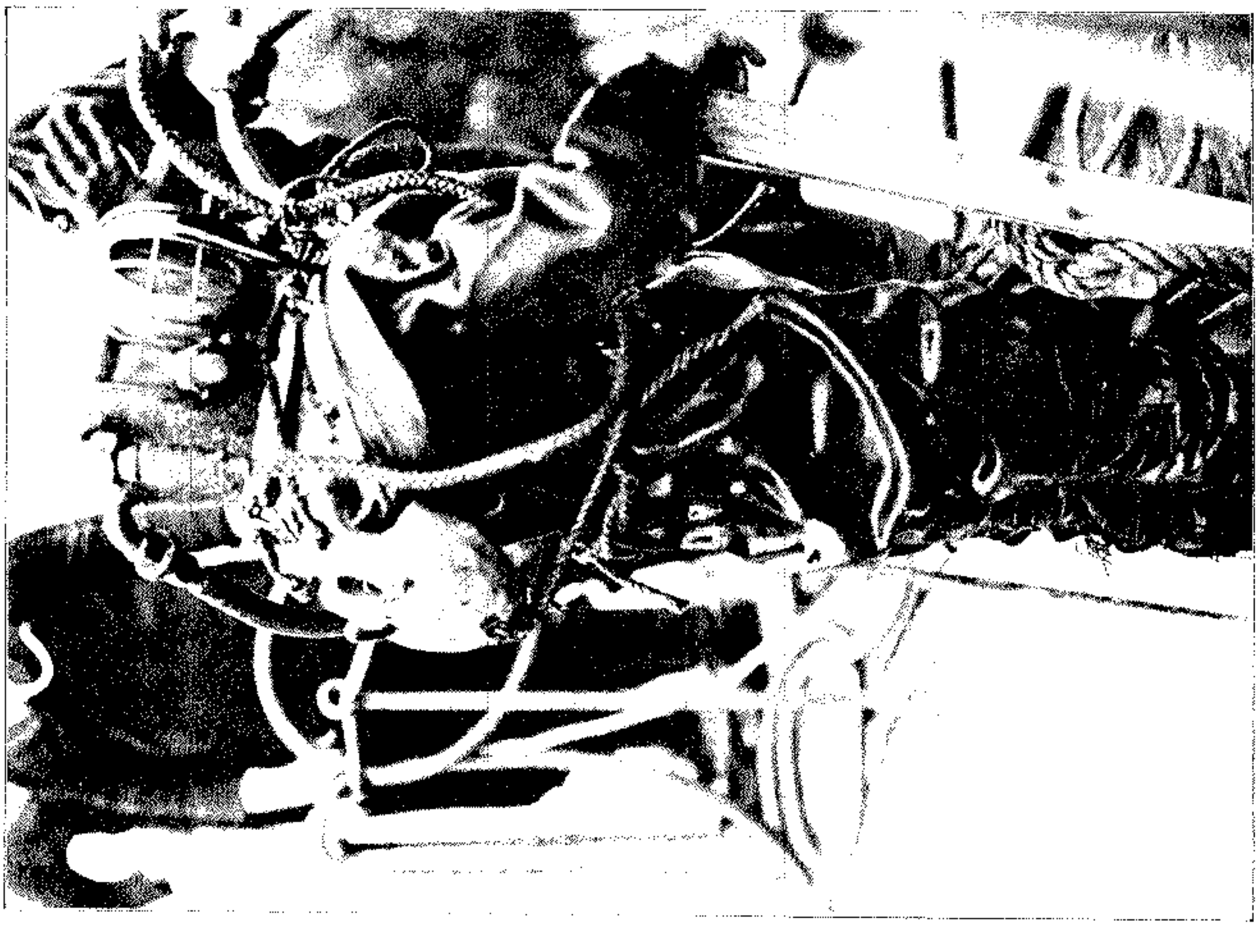


FIG. 3.—Photograph of diver who has ascended from just under water with the pump stopped. The dress is collapsed and closely applied to the body, as is always the case in the upright position under water.

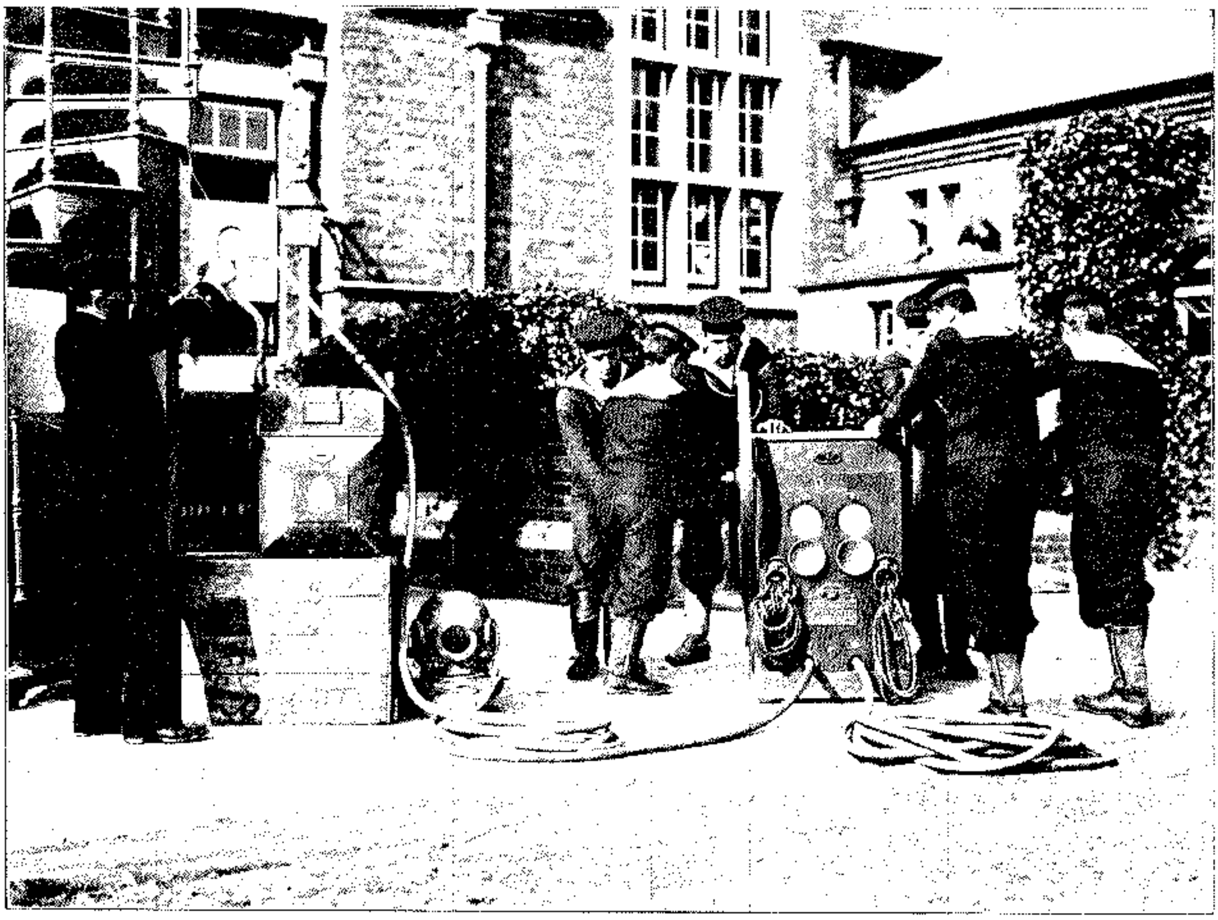


FIG. 4.—Service diving pump, with air-pipe connected to a gas-meter to test the leakage of the pump at different pressures. The clamp on the air-pipe is being adjusted so as to give the required pressure as shown by the gauge.

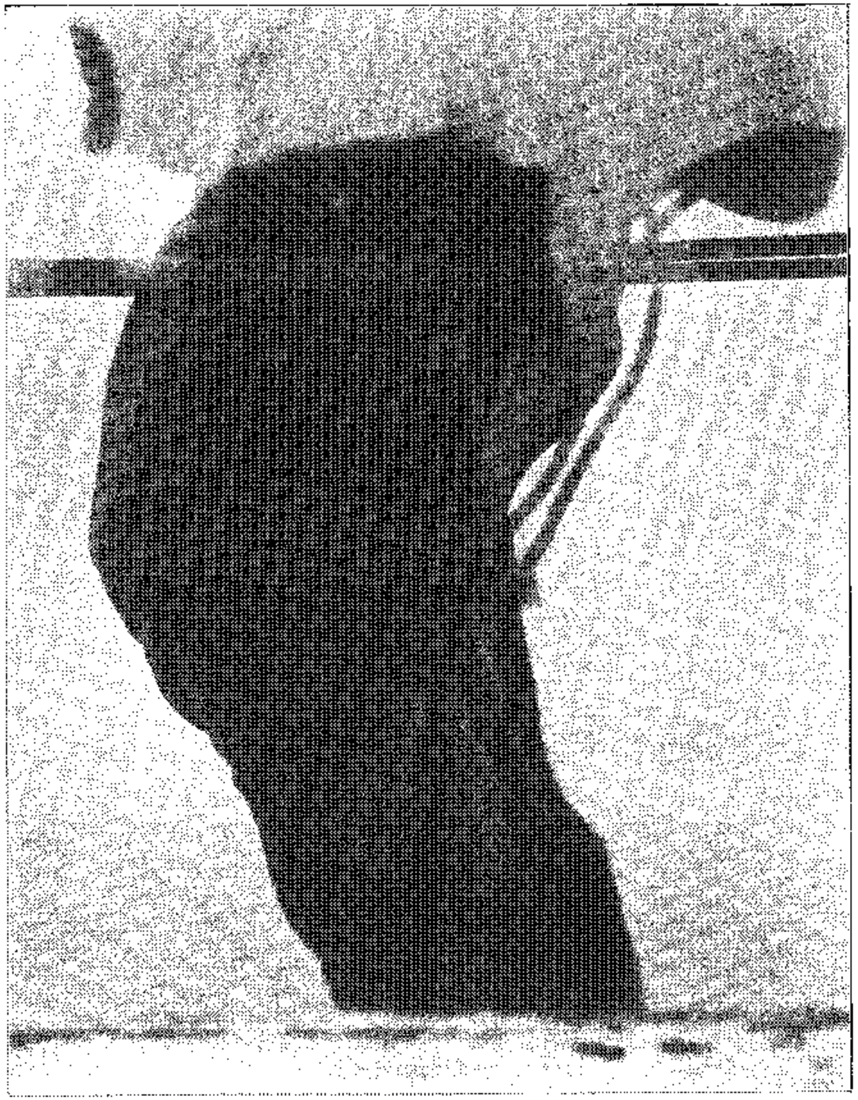


Fig. 5.—Photograph taken through a window of the experimental diving tank, showing how closely the diving dress is applied to the diver's limbs and body under water.

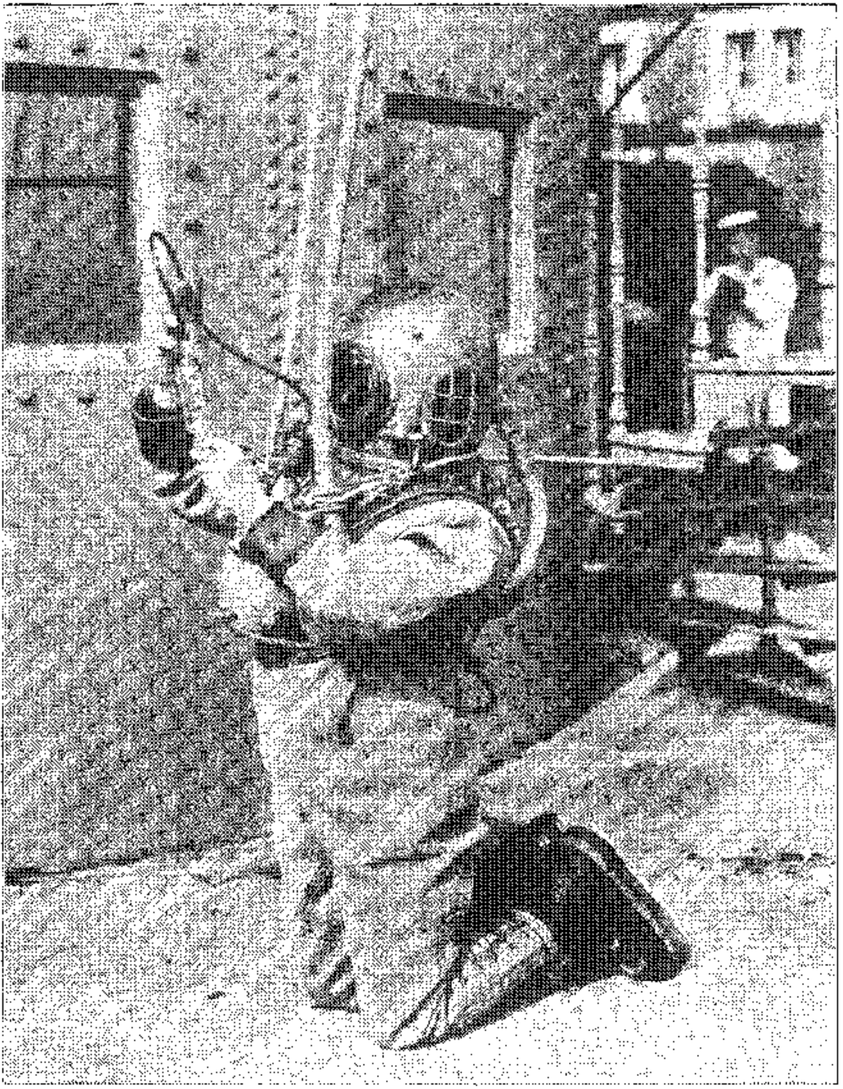


Fig. 6.—Showing method of taking a sample of air from the helmet of the diving dress. The experimental tank is seen in the background.

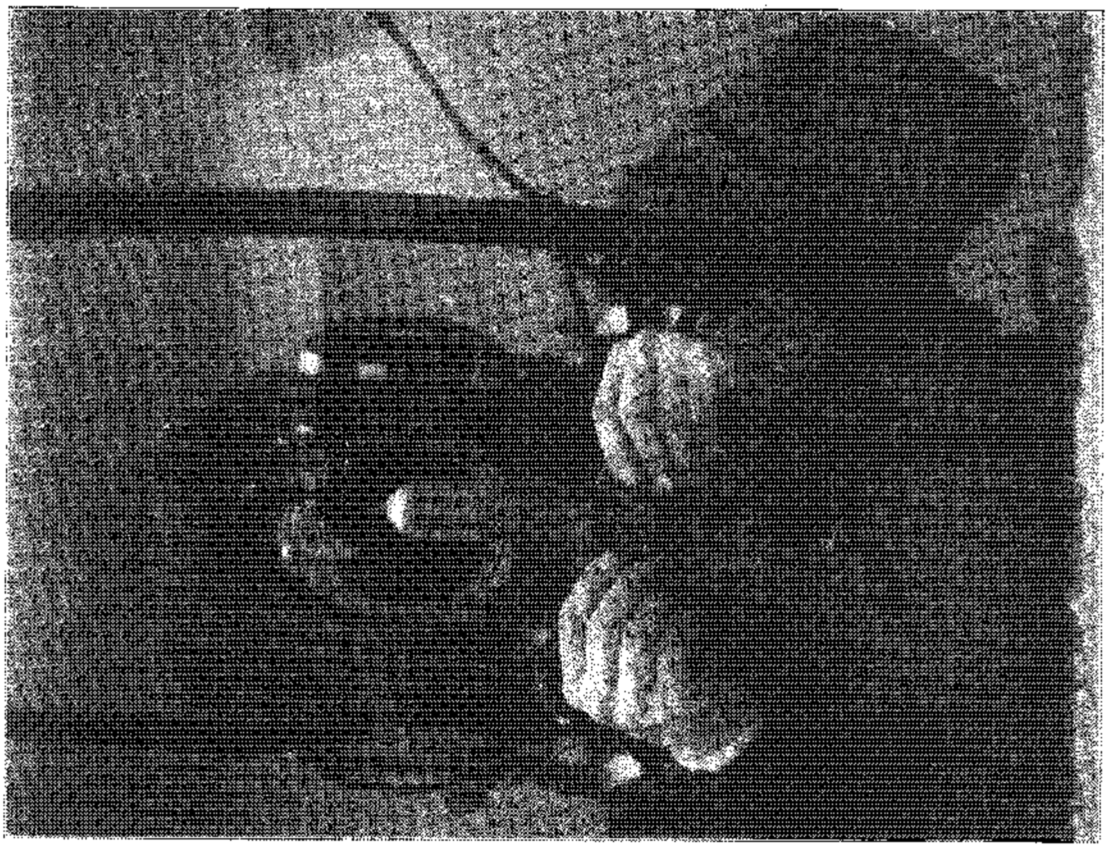


FIG. 7.—Photograph through the window of the experimental diving tank. Diver taking a sample of air from the helmet.

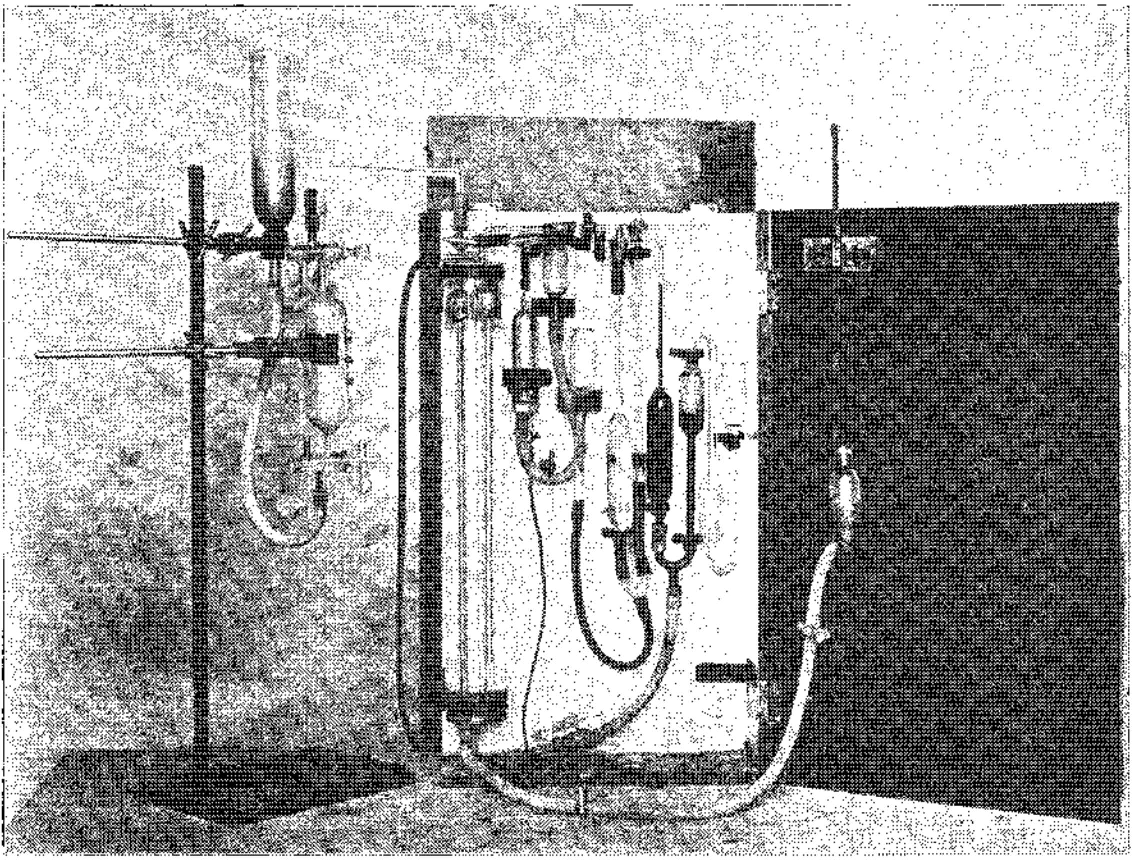


FIG. 8.—Portable gas analysis apparatus used in the experiments. The photograph also shows the method of connecting the sampling tube with the gas-burette. On ship board, if the vessel is not steady, the two screw clips seen on the rubber tube connecting the lower end of the gas burette with the mercury reservoir are moved close up to the gas burette and used in the manner described in the text.

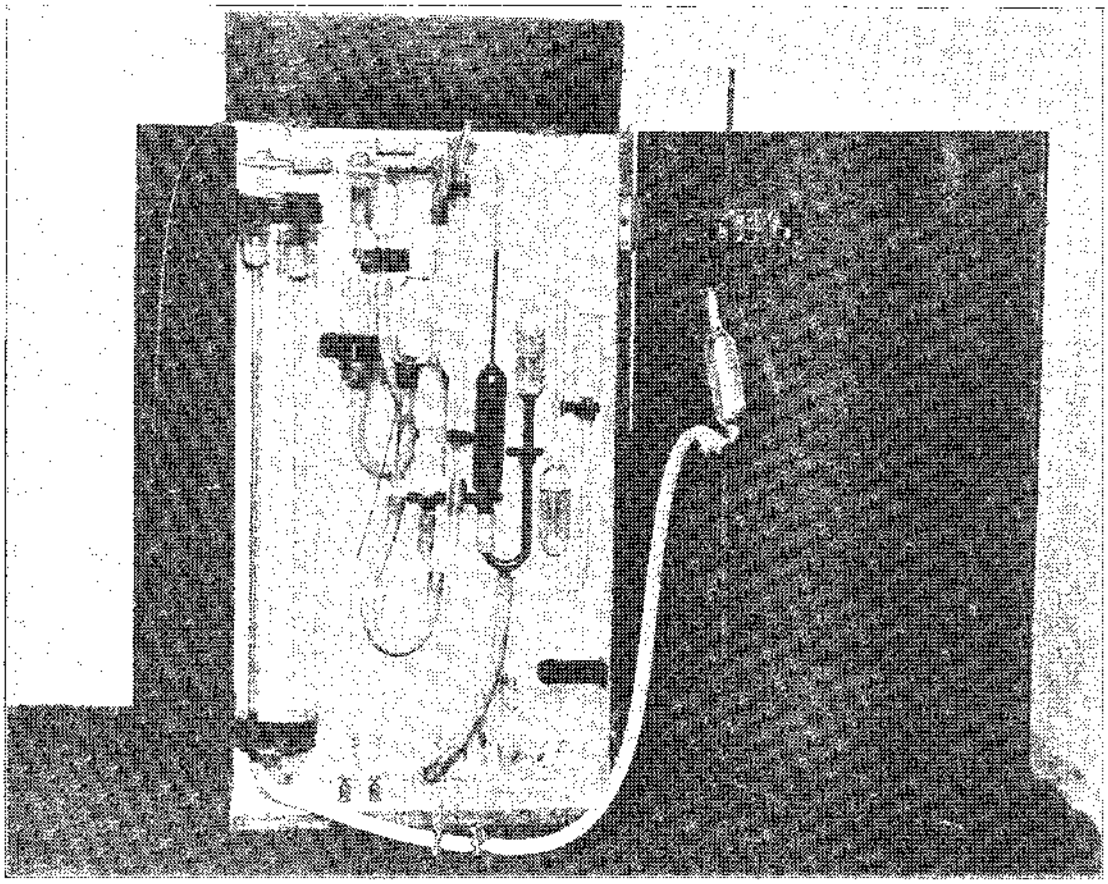


FIG. 8A.—Gas analysis apparatus.

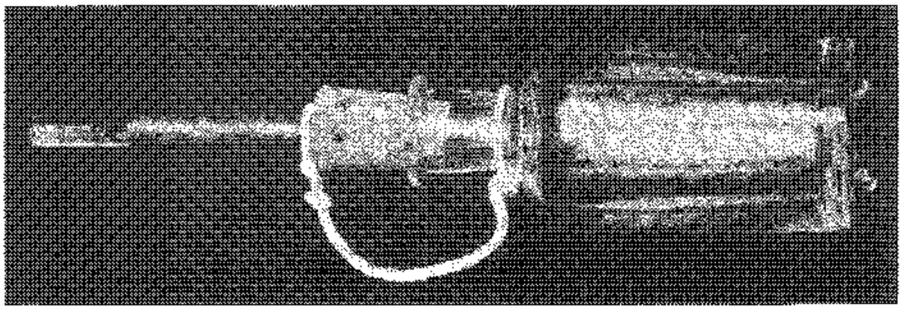


FIG. 9.—Bottle fitted up for rapidly taking samples of air in deep water. As the diver comes up to surface the excess of air in the bottle escapes through the slit seen in the rubber tube attached to the glass tubing passing through the cork.

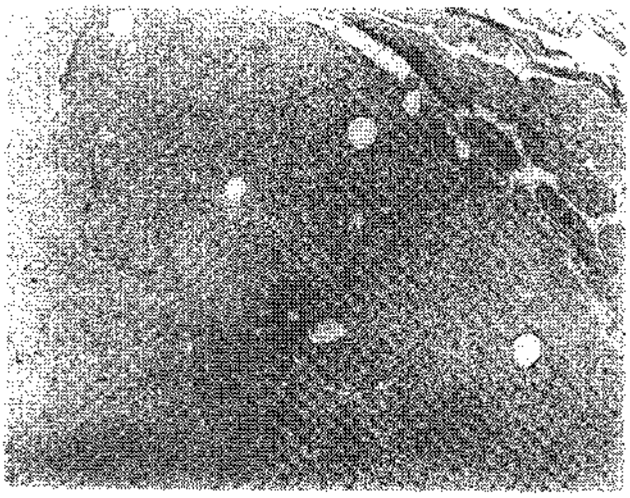


FIG. 10.

Micro-photograph of Section of Spinal Cord of goat killed by Sudden decompression. A number of air bubbles can be seen in the white matter, one being just at the junction of White and Grey Matter.

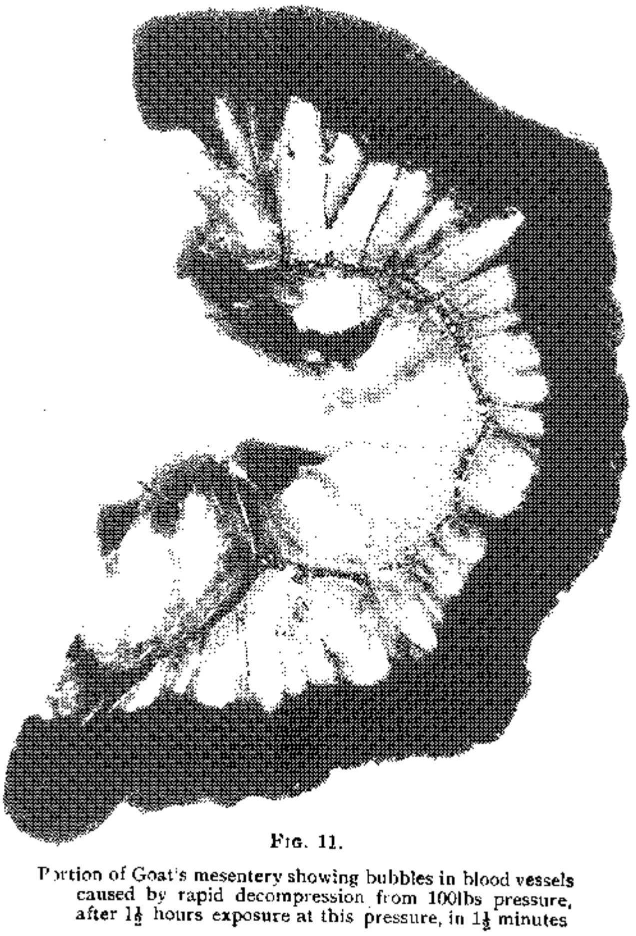


FIG. 11.

Portion of Goat's mesentery showing bubbles in blood vessels caused by rapid decompression from 100lbs pressure, after 1½ hours exposure at this pressure, in 1½ minutes

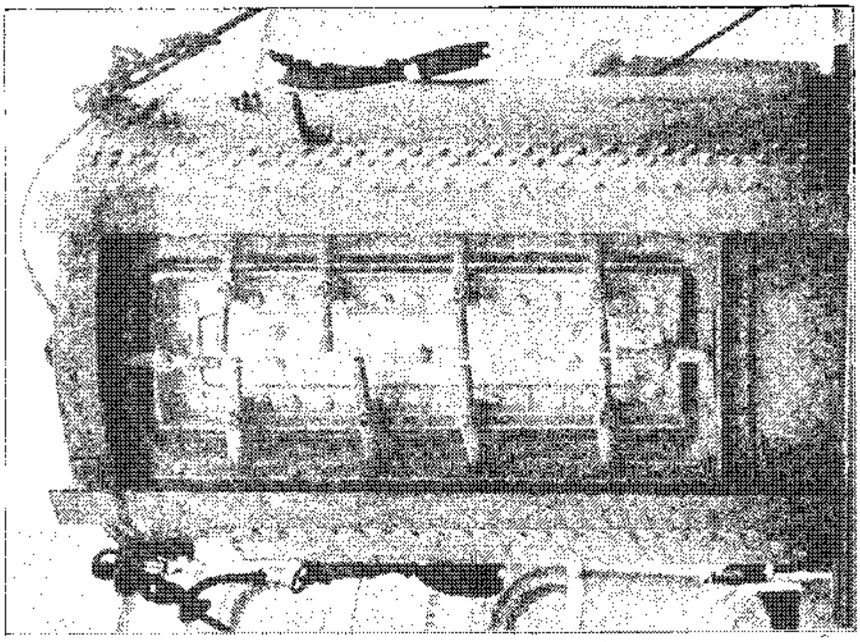


FIG. 12.—Steel chamber for re-compressing divers who show symptoms caused by liberation of air-bubbles in the blood or tissues. The chamber is also available for teaching divers to manage their ears under pressure.

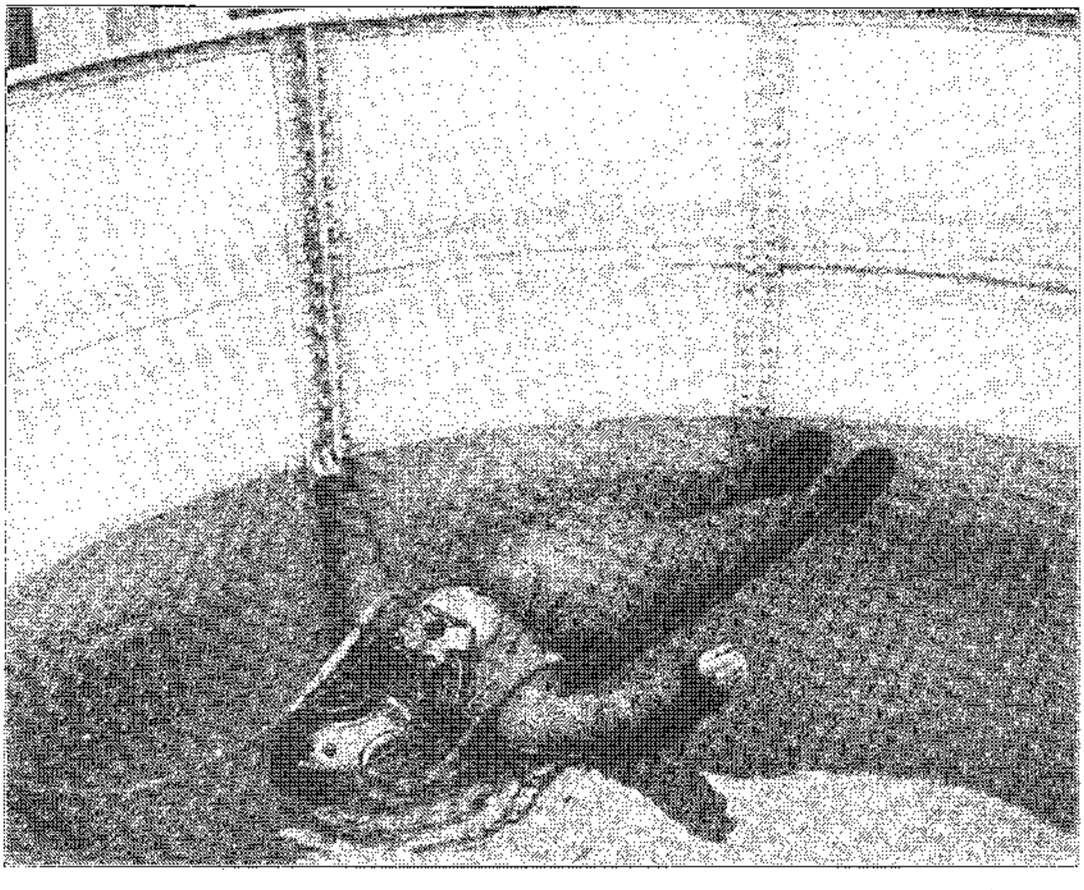


FIG. 13.—Diver blown to surface in ordinary diving dress. The diver cannot move his arms, and the air cannot escape, as his valve is below the water.

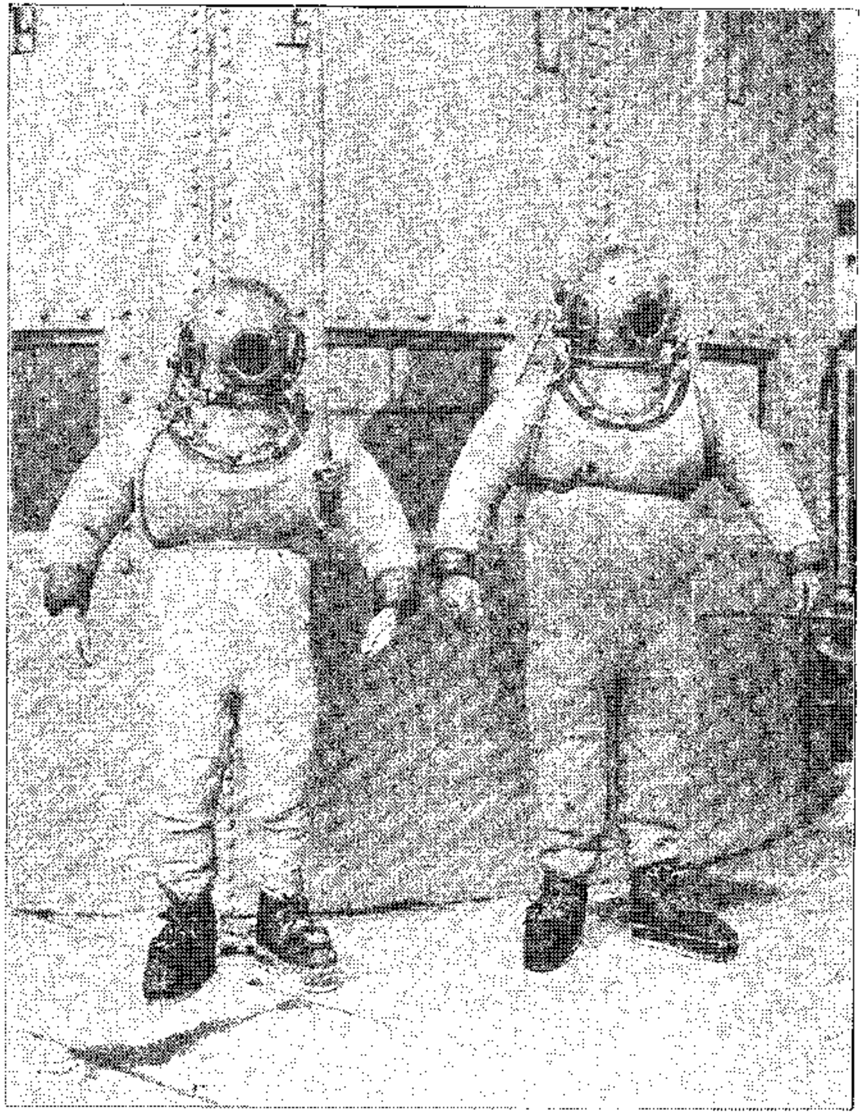


FIG. 14.—Diving dresses forcibly distended with air. The dress to the left has the legs laced up. The other dress is of the usual pattern.

Fig. 15.—Diver who has purposely blown himself up in the new pattern of dress, with the legs laced up. His head is upwards and his arms free. Compare Figure 13.

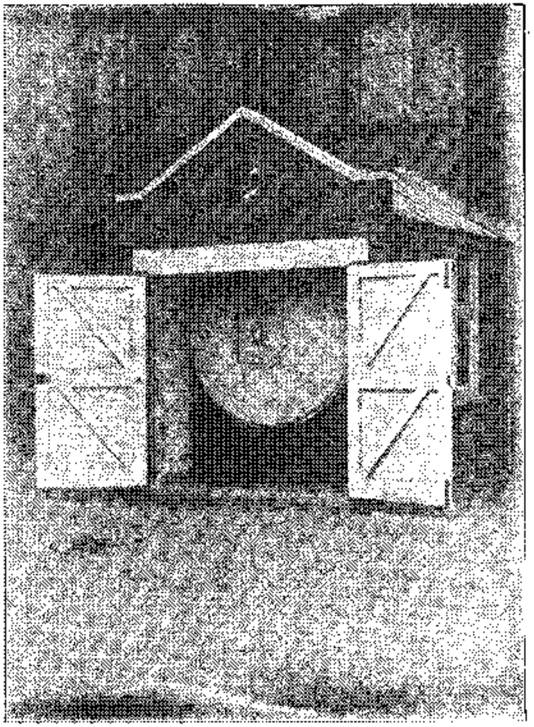


FIG. 16.—The steel chamber at the Lister Institute. View from outside, showing the back end of the chamber, with the large door and one inspection window.

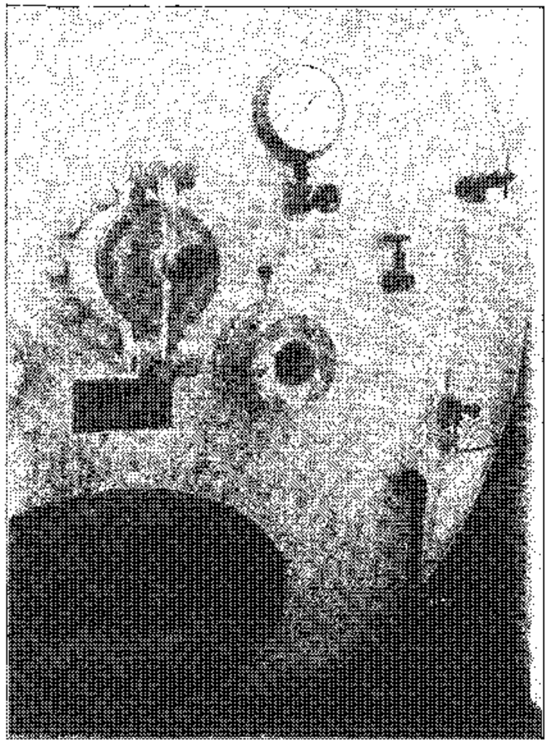


FIG. 17.—The steel chamber at the Lister Institute. Front end, showing the manhole for entering, the small air-lock for passing food, &c. into the chamber, an inspection window, a pressure gauge, and several valves, &c.

FIG 18. ARRANGEMENT FOR DOING MEASURED WORK UNDER WATER.

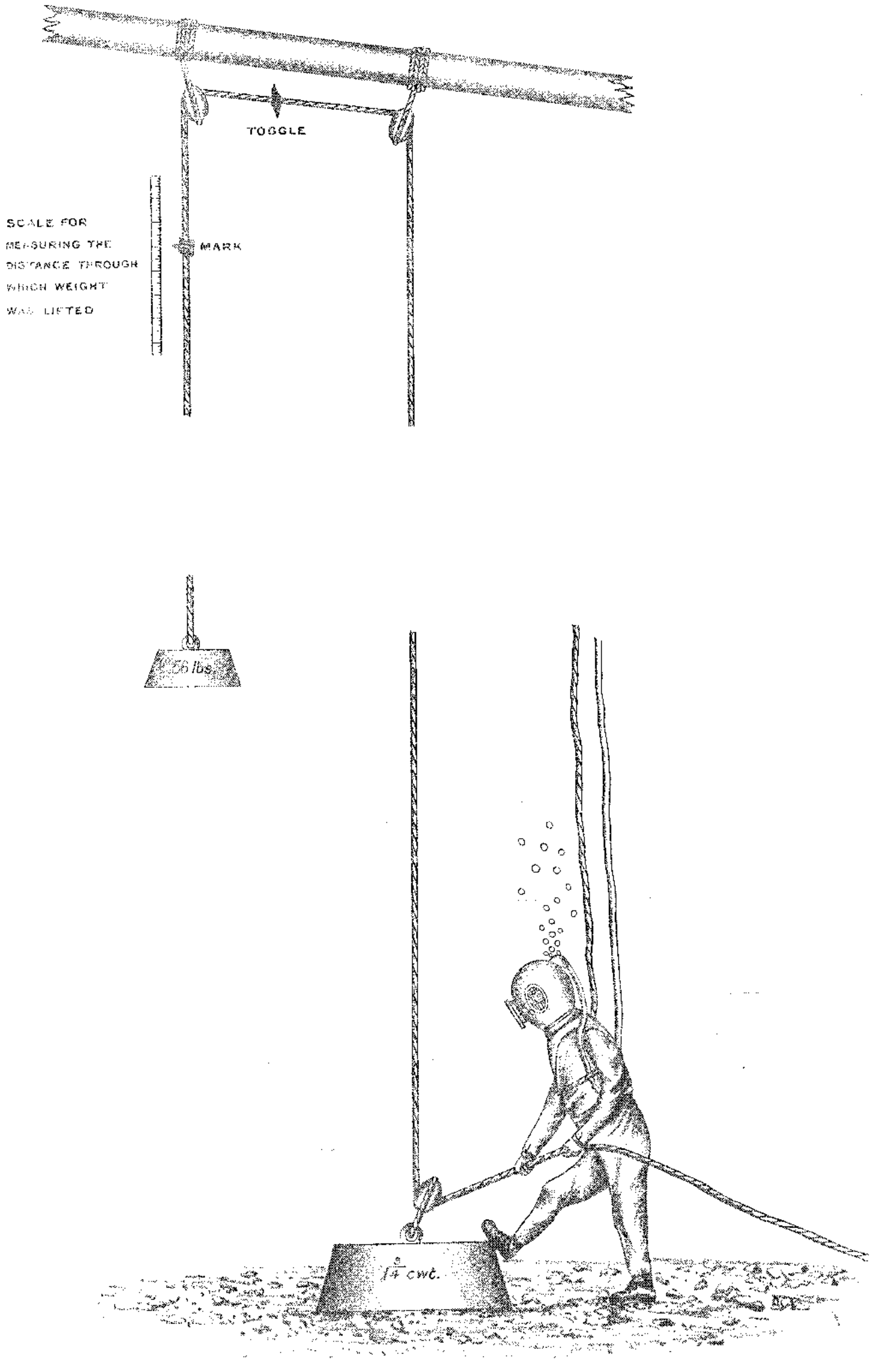
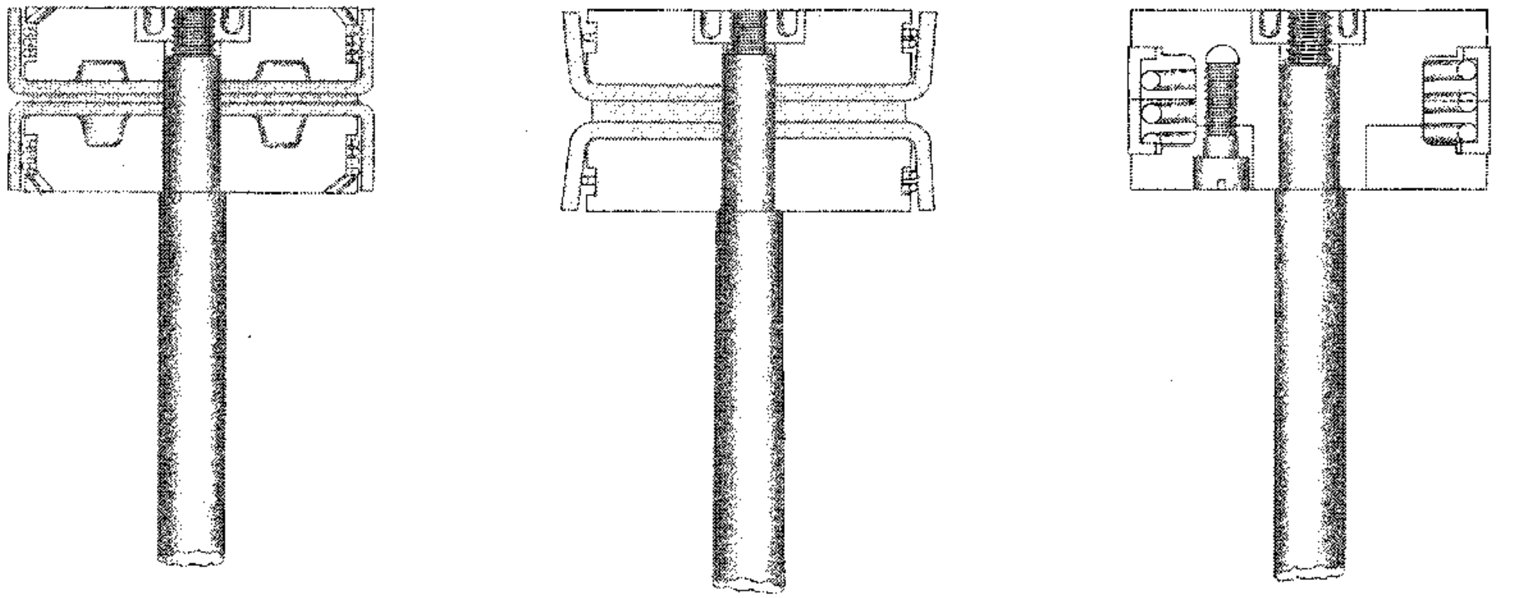


FIG. 19. DIFFERENT FORMS OF PISTONS USED IN PUMPS



IMPROVED LEATHER PISTON

OLD PATTERN LEATHER PISTON

ONE TYPE OF METAL PISTON

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FIG. 20.

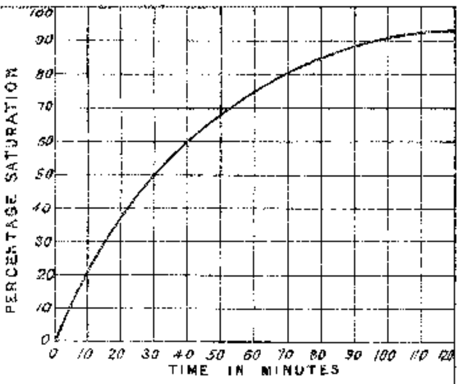

Fig.20. Curve showing approximate rate of saturation of parts of the body with an average rate of circulation and percentage of fat.

FIG. 21.

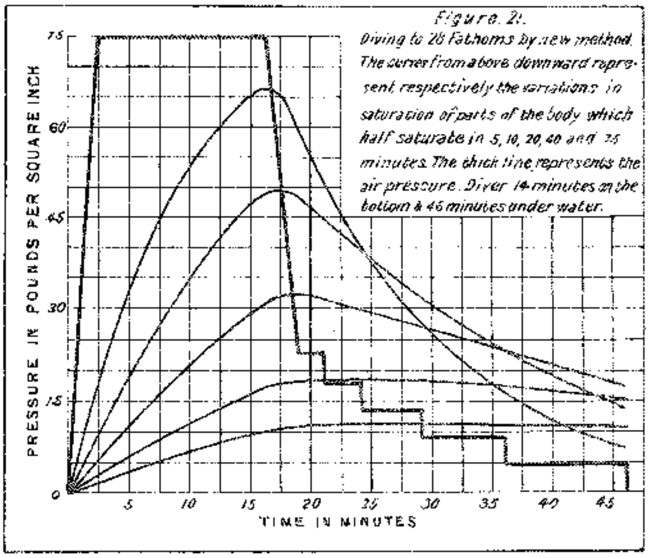

Figure. 21.
Diving to 28 fathoms by new method. The curves from above downward represent respectively the variations in saturation of parts of the body which half saturate in 5, 10, 20, 40 and 75 minutes. The thick line represents the air pressure. Diver 14 minutes on the bottom & 46 minutes under water.

FIG. 22.

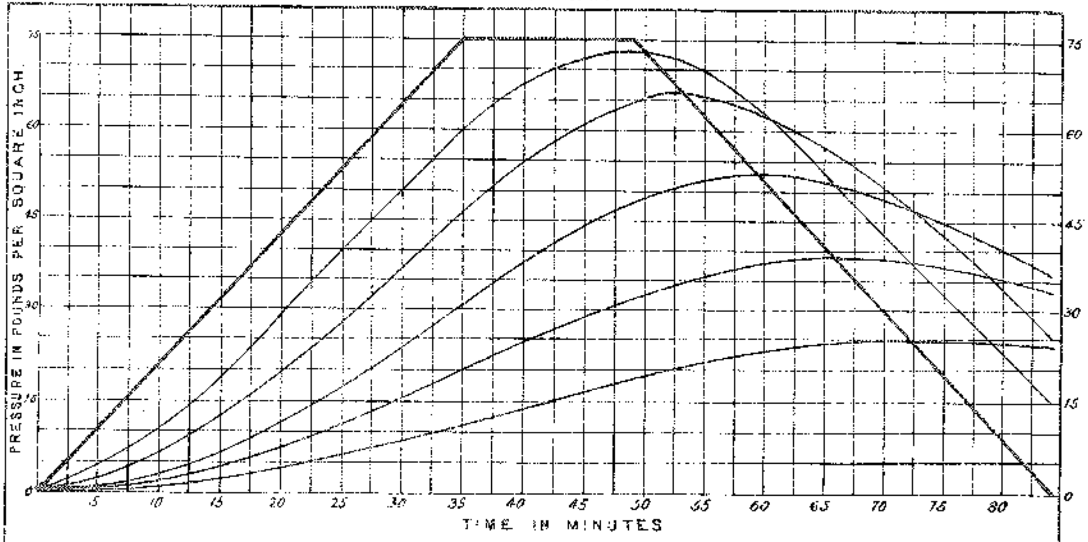

Figure 22. Diving to 28 fathoms by old method. The thick line represents the air pressure. The curves, from above downwards, represent respectively the variations in saturation of parts which half-saturate in 5, 10 20, 40, and 75 minutes.

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